A HOLISTIC APPROACH TO UNDERWATER SENSOR NETWORK DESIGN

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SYNOPSIS

Terrestrial wireless sensor networks with fixed and mobile nodes were initially developed for military applications such as battlefield surveillance and are now commonplace in many industrial and civilian application areas. It is easy to appreciate that such networks could be of immense value for military and civilian underwater tasks such as surveillance, monitoring and surveying. Autonomous underwater platforms and sensor systems have already found many applications in marine research, oceanography, marine commercial operations, offshore oil industry and defense. However, due to performance limitations of available underwater communication technologies, it is often impractical to network these sensor systems and to transmit the collected data underwater. Instead, the sensor systems have to be brought to the surface before the data can be downloaded. This is not only inconvenient, but also often costly. Since the data from the sensors is unavailable in real-time, it cannot be used effectively for adaptive sensing or for real-time decision-making. In this paper, we briefly review various technologies that have been developed for underwater communications & networking. We show that there are some fundamental differences between the challenges faced by the underwater systems, as compared to their terrestrial wireless counterparts; these differences impose some limitations and open up some opportunities. It is important to recognize that while underwater and terrestrial wireless sensor networks may share some similarities, the differences between the two warrant fundamentally different solution strategies to be adopted in the design of underwater sensor networks. We illustrate some solution strategies that can be implemented using currently available technology, and outline upcoming technological developments that might make underwater wireless sensor networks pervasive in the not-so-distant future.

1. INTRODUCTION

The combination of micro-electro-mechanical systems (MEMS), digital electronics and wireless communication technology gave rise to the concept of wireless sensor networks (Akyildiz et al. 2002). Such networks usually consist of a large number of sensor nodes, which are densely deployed either inside the phenomenon to sense or very close to it. The positions of the nodes may not need to be engineered or pre-determined, allowing random and rapid deployment. The nodes cooperate to sense the phenomenon of interest, to process the collected data and to communicate the data to the user via a set of sink nodes. Although the realization of wireless sensor networks often require the use of wireless ad hoc networking techniques, sensor networks warrant different design considerations than traditional ad hoc networks due to the higher node density, higher node failure rates and more stringent power and cost budgets. Wireless sensor networks have found military applications in equipment monitoring, battlefield surveillance, reconnaissance, and nuclear/chemical/biological attack detection. They have also found wide civilian applications in environmental monitoring, disaster warning, medicine and home automation.

The ocean is a difficult environment to operate in, sense, survey and monitor. The idea of deploying wireless sensor networks in the ocean to help sense, survey and monitor phenomenon of interest is attractive to navies, maritime operators, environment monitoring agencies, offshore industry and scientific researchers. However, the technologies, protocols and algorithms developed for terrestrial wireless sensor networks are surprisingly difficult to apply to marine sensing applications, as the ocean offers some fundamentally different challenges and opportunities.

Electromagnetic waves are rapidly absorbed by seawater, and therefore traditional wireless communication technology cannot be used underwater, except for very short-range communications. Sound waves propagate over long distances in water, and hence they are a natural means of communication over medium-to-long ranges, but offer some significant challenges (Chitre et al. 2008):

- Sound travels roughly 200,000 times slower than radio waves and gives rise to non-negligible propagation delays in underwater networks.
- The acoustic bandwidth available is range-dependent and typically several orders of magnitude lower than for radio communications, and therefore the network protocols and algorithms have to be much more frugal with data transmission.
- The acoustic communication channel often has a long delay spread, varies rapidly with time and has wide-band Doppler. Communication techniques to deal with such a channel are computationally more demanding, and offer lower data transmission rates and higher packet loss as compared to terrestrial wireless technologies.
- The power requirements for acoustic transmissions are higher than typical radio transmitters for comparable transmission ranges.

All of these factors, along with the cost/complexity of underwater housings, logistics of operations and deployment, make the design of underwater sensor networks significantly different from the design of wireless sensor networks. In this paper, we argue that an effective underwater sensor network design requires a holistic view of the sensing mission to be undertaken. The sensing strategy, data processing, placement of static sensor nodes and path planning for mobile sensor nodes have to be developed taking the communication constraints and networking performance into account. The network stack, the sensing data processing system and the nodes command & control system need to actively exchange information in order to achieve the sensing mission. In order to achieve realize such a network, the underwater sensor nodes may have to be much more capable and smarter than the corresponding wireless sensor nodes. We outline some of the design strategies for underwater sensor networks and review current and upcoming technologies that may play a key role in such networks.

2. DISTRIBUTED MARINE SENSING

The concept of using a distributed set of sensors to sense a marine phenomenon is not new. In this section, we briefly review two practical distributed wireless marine sensing networks.

2.1. Argo Floats

Argo is an international collaboration that collects temperature, salinity and current data globally (http://www.argo.ucsd.edu). The data come from battery-powered autonomous *Argo floats* that spend most of their life drifting at a parking depth. They are stabilized by being neutrally buoyant at the parking depth pressure by having a density equal to the ambient pressure and a compressibility that is less than that of seawater. Every 10 days or so, the floats pump fluid into an external bladder and rise to the surface slowly while measuring temperature and salinity. Satellites determine the position of the floats when they surface, and receive the data transmitted by the floats. The bladder then deflates and the float returns to its original density and sinks to drift until the cycle is repeated. Each float is designed to make approximately 150 such cycles.

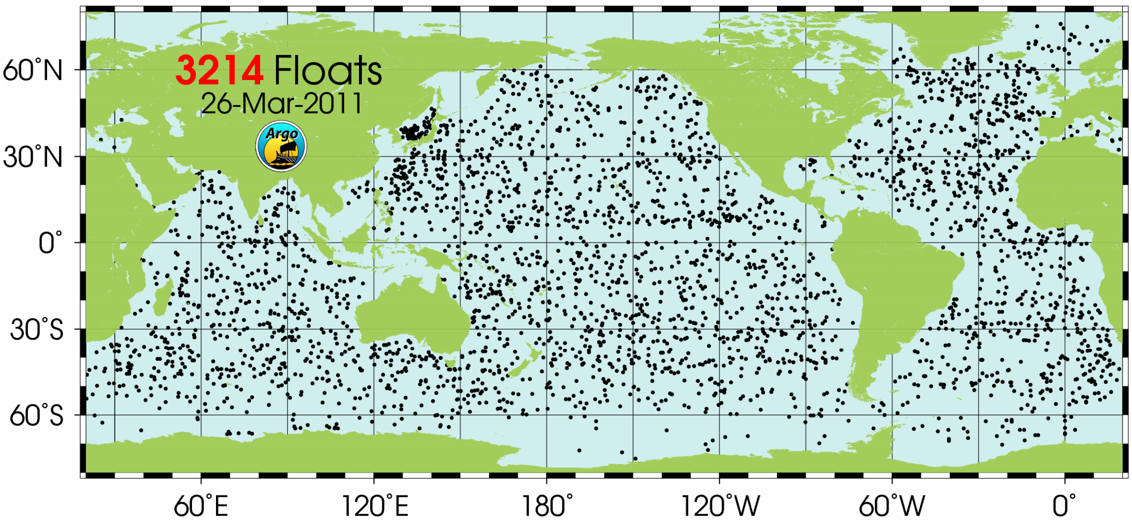


Figure 1: A map showing the location of 3,214 Argo floats in service as of 26 March 2011. These data were collected and made freely available by the International Argo Project and the national programs that contribute to it. Argo is a pilot program of the Global Ocean Observing System.

The Argo floats in service are shown in Figure 1. Although these floats represent a large number of sensor nodes in a successful global marine sensing network, the do not form an underwater sensing network. The sensor nodes do not communicate among each other, and only communicate to the data centers via satellite when the surface every 10 days. Since the sensing mission does not demand real-time access to the collected data, the designers of the Argo network were able to avoid the complexities of underwater communication & networking.

2.2. Sonobuoys

A sonobuoy is an expendable sonar system that is usually dropped from aircrafts or ships conducting anti-submarine warfare or underwater acoustic research (http://en.wikipedia.org/wiki/Sonobuoy). The buoy relays acoustic information from its hydrophones via UHF/VHF radio to operators onboard the aircraft. Active sonobuoys emit acoustic "pings" in the water and listen for echoes to detect targets. Passive sonobuoys do not emit sound but simply listen for sounds made by targets of interest. They may also be used as multi-static sonar receivers where the acoustic sources may be other active sonobuoys or depth charges. Sonobuoys may be deployed in large numbers to help with detection and localization of underwater targets such as submarines. Once detected, the targets can be localized via triangulation by combining the information from multiple sonobuoys.

Figure 2: Sonobuoy being loaded onto an USN P-3C Orion aircraft (Source: http://www.navy.mil/view_single.asp?id=32116)

Sonobuoys represent an rapidly deployable network of sensors that can help localize underwater targets. The sonobuoys do not communicate among each other, but only communicate with controlling aircrafts or ships, where the data is processed. Moreover, since sonobuoys are typically at the surface, they use radio communications and do not need underwater communications.

3. UNDERWATER SENSOR NETWORK DESIGN

Although both examples we reviewed in the previous section are not underwater sensor networks, they clearly demonstrate the potential applications of distributed sensing in a marine context. Depending on the phenomenon being sensed, sensor nodes such as the Argo floats may benefit from underwater networking technology. For example, if such floats were able to detect seismic activity and small changes in water level, they could be used for Tsunami detection and early warning. In order to decide whether a locally detected event warrants an alarm, the nodes would have to communicate with other nodes and exchange data underwater. It is also not difficult to envision an underwater network of rapidly deployable sensor nodes like the Sonobuoys that sink to the sea bed. Such networks could be used for underwater target detection, environmental monitoring, seismic monitoring, etc. The technological limitations on underwater communication and networking currently limit our ability to deploy such underwater sensor networks. In the following sections, we will look at the challenges involved and some potential solutions.

3.1. Mission planning with communication constraints

In wireless sensor network analysis, researchers often assume a monotonic decrease of communication ability with distance. Due to the complex acoustic propagation environment encountered underwater, this is often not true (Chitre, 2006; Preisig, 2007). As a first approximation, the signal-to-noise ratio (SNR) varies with distance and depths of the transmitting and receiving nodes. The ability to communication depends on the SNR, and therefore the placement and motion of sensor nodes critically affects their ability to communicate with each other. The performance of an underwater network, where the node placement and motion is purely dictated by the sensing task, may be poor. If communication is a critical factor in the success of the sensing mission, then it is important that the placement and motion planning of the sensor nodes take communication performance into account. Small changes in depth of location of a sensor may be insignificant in terms of the sensor data to be collected, but might make a large difference to the communication ability of a node, or the transmission power required to successfully communicate. Since power availability is low, and communication resources are scarce, sensing and communication consideration need to be at par when designing an underwater sensor network.

In recent years, adaptive and cooperative sensing in an underwater environment has become an area of intense research (Das et al. 2010; Rajan et al. 2009; Chitre, 2010). Agent based command and control (C2) architectures such as the T-REX (McGann et al. 2007) and STARFISH (Tan et al. 2010) are designed to take in sensor data and integrate the knowledge gained into the motion planning of the underwater nodes. Such agent based architectures may be well suited to incorporate communication models into the motion planning, and may form the basis of future underwater sensor networks (see Figure 3).

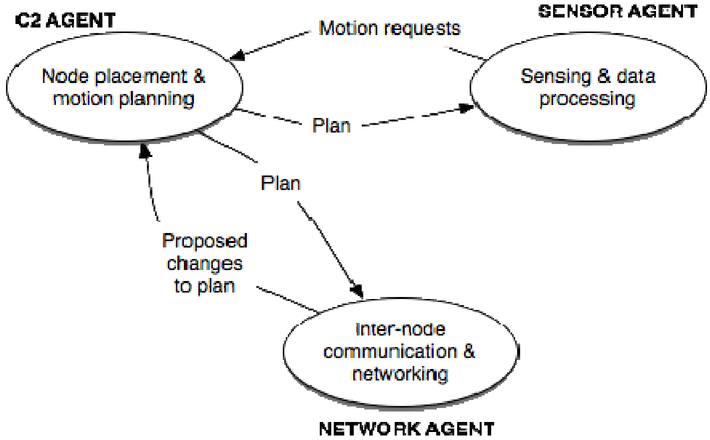
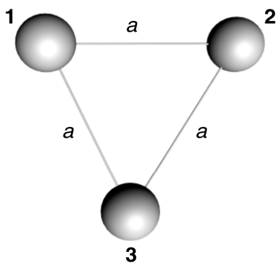


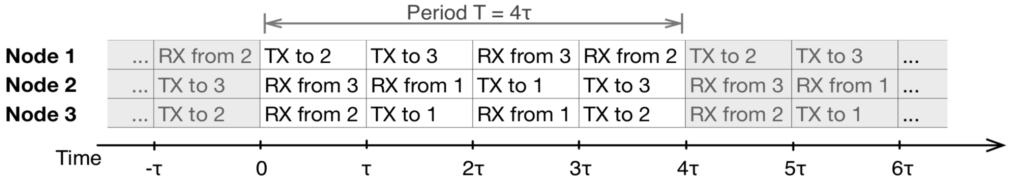
Figure 3: An outline of a multi-agent holistic command and control system for underwater sensor nodes.

3.2. Long propagation delays

Radio waves travel at approximately 3×10^8 m/s, while sound waves in water propagate at about 1,500 m/s. The ill effects of large propagation delay have been extensively studied. The performance of handshaking protocols and acknowledgment based retransmission schemes is known to suffer due to the long two-way propagation times (Leon-Garcia and Widjaja, 2004). A lot of effort has been expended to mitigate the ill effects of non-negligible propagation delay in underwater networks (Guo et al. 2009; Hou et al. 1999; Kredo et al. 2009; Peleato and Stojanovic, 2007; Syed et al. 2008). However, we believe that long propagation delays provide a rather untapped opportunity in underwater networks.



(a) Geometry for a 3-node equilateral triangle network



(b) Periodic schedule

Figure 4: A 3-node equilateral triangle network and its transmission schedule. An entry "TX to j" means a transmit to node j in that time slot, while an entry "RX from i" means receive from node i in that time slot. The length τ of each slot is equal to the propagation delay between nodes, i.e., τ = a/c, where c is the speed of sound. (Source: Chitre et al. 2010)

To understand this, let us consider three sensor nodes forming an equilateral triangle as shown in Figure 4(a). Assuming all three nodes are able to hear each other and use the same frequency band to transmit, a typical medium access control (MAC) protocol has to ensure that only one of the three nodes transmits at a given time. If more than one nodes transmit simultaneously, the signals overlap at the receiving node and neither signal leads to a successfully received packet. This is termed as a *collision*, and the geographical area in which nodes can potentially interfere with each other is known as a *collision domain*. As the number of nodes in a single collision domain increases, each node, on an average, gets to transmit less often. For a *N*-node network, the throughput per node is inversely proportional to *N*. With non-negligible propagation delay, it is not necessary to forbid multiple nodes from transmitting simultaneously – we only require than an unintended transmission not reach a node while it is receiving a packet. It turns out that it is indeed possible to carefully design a schedule for a given geometry such that roughly half the nodes in a collision domain can transmit simultaneously without causing collisions (Chitre et al. 2010, 2011). One such schedule of the three node equilateral network is shown in Figure 4(b). The schedule repeats every 4 time slots, and has 6 transmissions per period. So, for a 3-node network, we can have an average of 1.5 transmissions per time slot. For a general *N*-node network, a carefully designed schedule may be able to transmit up to *N*/2 packets per time slot. This is a very significant improvement over the no propagation delay case, where it is not possible to transmit more than 1 packet per time slot.

Although this idea presents an opportunity for high throughput in a sensor network with propagation delays, the opportunity can only be realized through careful planning of the inter-node distances and transmission schedules. In an application where the node placement is purely dictated by the sensing task, or by ease of deployment, may not be able to take advantage of this opportunity. In underwater networks, data rates are low and bandwidth is a scarce resource – it is thus important the opportunity not be ignored. In order to do this, the node placement has to take the network protocol and scheduling constraints into account. With potentially small changes in node placement, with have insignificant effects on the sensing or ease of deployment, an underwater sensor network may be able to achieve much higher communication throughput. In adaptive mobile networks, the holistic C2 architecture proposed in the previous section can take inputs from the network stack to help guide motion planning decisions.

3.3. Heterogeneous sensor nodes and hybrid approaches

Since underwater communication constrains underwater sensor networks severely, when possible, it is worth exploring hybrid approaches to networking. For example, although sensor nodes may be submerged and therefore unable to communicate to each other via radio waves, it may be possible to have a *gateway node* at the surface that communicates to a *cluster* of underwater sensor nodes using acoustics but with other clusters using radio waves. One such example deployment scenario is depicted in Figure 5.

Another example of a hybrid network is one where underwater acoustic and optical links are used cooperatively. Underwater acoustic communications offer medium-to-long range communication at relatively low data rates. On the other hand, optical communications in water can achieve high data rates at short ranges (Doniec et al. 2010). By combining both communication capabilities with a specialized "*data mule*" node, we can get an effective heterogeneous underwater sensor network. The data mule node communicates with sensor nodes and locates them underwater using the low-speed acoustic links. When it approaches a sensor node, it switches to the high-speed optical link to download data from it, or transfer data to it. It then moves from sensor node to sensor node, thus effecting high-speed high-latency communication between nodes. When the application is tolerant to high latency communications, this approach may be more power efficient than a network with acoustic links transferring the data over long ranges.

4. SENSOR NODE TECHNOLOGY

In the previous section, we argued that underwater sensor nodes need to be smarter than typical wireless sensor nodes, as they need to take communication constraints into account explicitly. Other factors such as waterproofing, the ability to withstand high pressures at depth, ability to operate in strong currents and corrosive seawater, etc contribute to relatively high cost and size of underwater sensor nodes. A typical low-cost wireless sensor node may cost a few tens to hundreds of US$. On the other hand, a low-cost underwater sensor node may cost between a few thousand to few tens-of-thousand US$. This two-order magnitude difference in cost significantly changes the approach to underwater sensor networking. Rather than consider the sensor nodes as expendable, some thought should be given to the recovery of nodes. This is also an important consideration from an environmental viewpoint, as we should not litter our oceans with discarded sensor nodes. The power budget for acoustic transmission and propulsion (for mobile sensor nodes) is usually a significant part of the total power budget. Thus algorithms that may be considered computationally too intensive to put on wireless sensor nodes, may be considered reasonable for underwater sensor networks, as their power usage may only be a small fraction of the total power budget. In this section, we briefly review a few technologies that we consider promising for use as sensor nodes in heterogeneous underwater sensor networks.

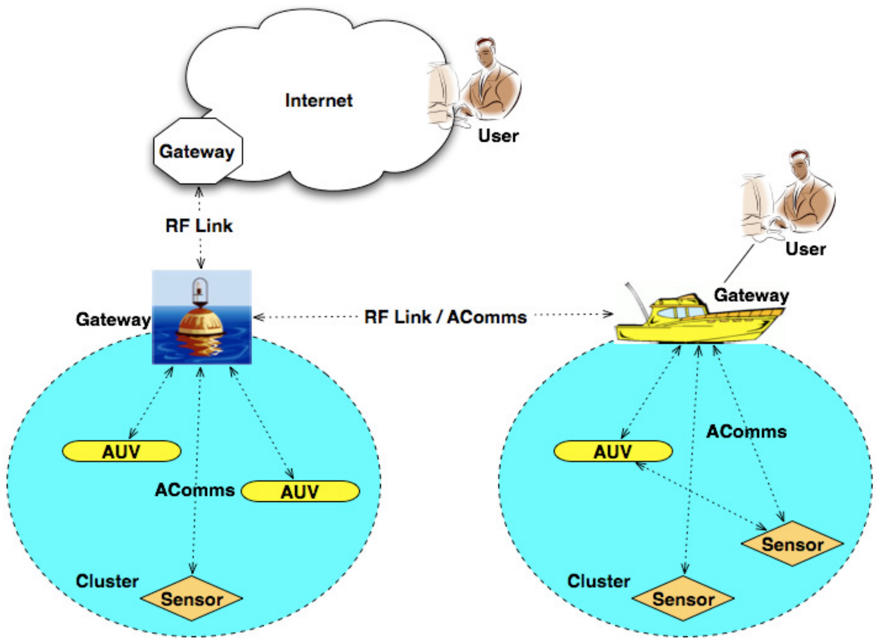


Figure 5: An illustration showing two clusters of sensor nodes networked together using a high-speed surface radio frequency (RF) link or a long-range acoustic link.

4.1. Fixed bottom-mounted sensor nodes

One of the characteristics of a sensor network is the ability to deploy one quickly on demand. To meet this requirement, we need sensor nodes that can be easily deployed from a surface vessel or an aircraft. Floating sensor nodes drift rapidly due to ocean currents and wind. In a fixed sensor node is desired, it has to be anchored to the seabed. At ARL, we have developed an underwater sensor node knows as the PANDA, that can be deployed and recovered from a boat without diver support (Koay et al. 2002). The PANDA unit logically consists of 3 parts – the electronics & sensing sub-system, the anchoring sub-system and the recovery sub-system. The anchoring sub-system usually consists of an anchor, anchor-chain and a line connecting it to the other sub-systems. The recovery sub-system is a buoy that provides buoyancy during recovery with a recovery line wrapped around it. The line is connected to a release pin, which is held by a mechanical jaw in the recovery buoy. When the sensor node wishes to surface, it opens the jaw and releases the pin. This allows the buoy to unroll the recovery line and surface under its own buoyancy. It remains connected to the other sub-systems with the line, and therefore all sub-systems can be recovered from a boat at the end of the sensing mission. The electronics & sensing sub-system consists of batteries, data acquisition computer, data storage device, power management unit, sensors, signal conditioning circuitry and an acoustic communications modem. Physically this can be in a separate mechanical compartment (UNET-PANDA design – Figure 6) or integrated with the recovery buoy (A-PANDA design). The PANDA sensor nodes have been successfully used in the form of a simple proof-of-concept sensor network that was used for ship tracking (Koay et al. 2006).

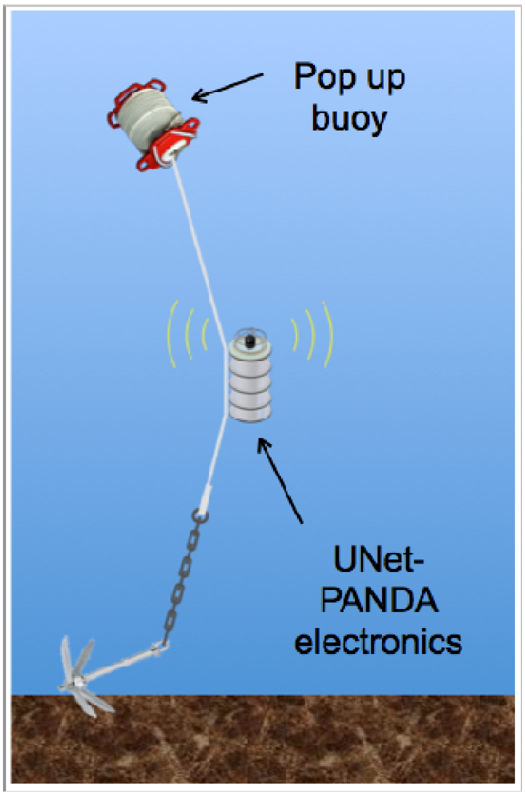


Figure 6: A schematic representation of the UNET-PANDA design showing the anchoring, electronics & sensing and the recovery (pop-up buoy) sub-systems.

4.2. Mobile sensor nodes

Underwater sensor networks may also comprise of mobile nodes. These nodes may include drifters and autonomous underwater vehicles (AUV). Drifters such as the Argo floats use natural water movement to achieve motion. While they are at the mercy of the water currents, they can achieve very low power consumption and therefore long endurance. On the other hand AUVs are capable of generating their own motion using a combination of thrusters, buoyancy pumps and control surfaces. AUVs usually have relatively short endurance due to the power demands of the motion generating sub-systems.

In the past two decades, a new type of underwater vehicle known as a glider has been developed (Webb et al. 2002). Gliders use buoyancy changes to change depth, and use control surfaces to convert the vertical motion into a forward thrust. The buoyancy changes can be driven by small pumps, or using thermal energy in the ocean. Since gliders avoid the use of propulsion sub-systems with high power demands, they have much longer endurance than typical AUVs. They are much slower than AUVs and have much lesser control over their motion. They provide an interesting intermediate between purely drifting floaters and completely self-propelled AUVs, with endurance comparable to floaters with a fair degree of control over their motion. Gliders typically need deep water for operation. GraalTech has developed a hybrid shallow-water glider-AUV known as the Folaga (Caffaz et al. 2010). In collaboration with GraalTech, NURC and ISME, we enhanced the Folaga to accept payload modules. The enhanced Folaga is known as the eFolaga. The first payload module that was developed and tested on the eFolaga is an acoustic communications modem module, allowing the eFolaga to become an underwater sensor node (Figure 7). NURC intends to use the eFolaga as a sensor node for cooperative anti-submarine warfare (C-ASW) (Been et al. 2010).

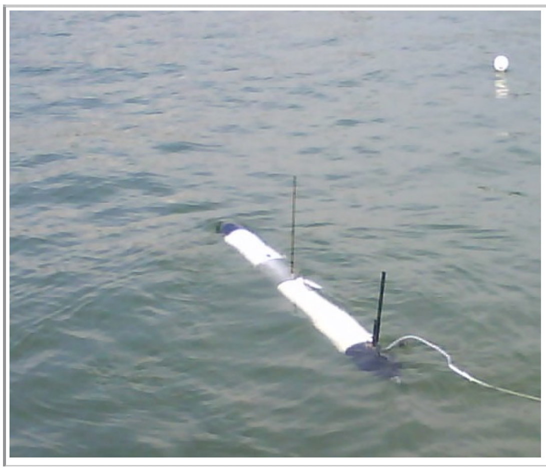


Figure 7: The eFolaga AUV installed with the ARL acoustic communications modem.

The Australian National University (ANU) has developed a small AUV known as the Serafina (http://serafina.anu.edu.au/Publications/Serafina.06.pdf) as a test bed for cooperative sensing using the AUVs. The Serafina has very short-range communication capability, and therefore is an appropriate AUV for use as a sensor node in dense underwater sensor networks.

4.3. Energy harvesting

Wireless sensor nodes can extend their endurance by extracting energy from their surroundings. One of the most common sources of energy for sensor nodes is solar (Raghunathan et al. 2005). Unfortunately underwater sensor nodes do not have direct access to solar energy, as sunlight does not penetrate seawater effectively. Although a solar AUV has been developed (Crimmins et al. 2006), it has to come to the surface to recharge. Bottom-mounted nodes may be able to harvest energy from the water flow due to currents. A device that generates power from water flow has been developed (Taylor et al. 2001). However, underwater energy harvesting solutions are still a long way away from a level of maturity needed for adoption in underwater sensor networks.

5. CONCLUSION

In this paper, we highlighted key differences between wireless sensor networks and underwater sensor networks. We reviewed some of the challenges faced in designing underwater sensor networks, and presented potential solution strategies. The solution strategies require a close cooperation between sensor data processing, node placement and motion planning and communication between the nodes. The communications/networking stack cannot be treated as a black-box service provider for the command & control and sensing tasks, but has to be considered holistically in a sensing strategy. We also reviewed current and upcoming technology components that are likely to be key to underwater sensor networks of the future.

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Mandar Chitre received B.Eng. and M.Eng. degrees in electrical engineering from the National University of Singapore (NUS), a M.Sc. degree in bioinformatics from the Nanyang Technological University (NTU) and a Ph.D. degree from NUS. After spending several years in the industry heading the technology division of a regional telecommunications solutions company, he came back to academia in 2003. He currently holds a joint appointment with the Tropical Marine Science Institute (TMSI) as the Head of the ARL, and with the Department of Electrical & Computer Engineering at NUS as an Assistant Professor. His current research interests are underwater communications, autonomous underwater vehicles, model-based signal processing and modeling of complex dynamic systems. He has served on the technical program committees of the IEEE OCEANS, WUWNet and DTA conferences, as served as reviewer for many international journals and is currently a guest editor for a special issue of the International Journal of Distributed Sensor Networks. He is also the vice chairman of the IEEE OES Singapore chapter and the IEEE technology committee co-chair of underwater communication, navigation & positioning.