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A Survey on Underwater Sensor Networks: Its Architecture, Hardware and Applications

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Abstract: *Underwater wireless sensor networks consist of a certain number of sensors and vehicles that interact to collect data and perform collaborative tasks. The sensor network consists of static and mobile underwater sensor nodes. The nodes communicate point-to-point using a novel high-speed optical communication system integrated into the TinyOS stack or other small operating system, and they broadcast using an acoustic protocol integrated in the OS stack. The sensor nodes have a variety of sensing capabilities, including cameras, water temperature, and pressure. The mobile nodes can locate and hover above the static nodes for data mulling, and they can perform network maintenance functions such as deployment of sensor nodes, relocation of sensor nodes, and recovery from failures. In this paper, we describe the networking and hardware architecture of underwater sensor network. We then describe the hardware architecture of underwater sensor node, types of nodes and finally we discuss the applications of underwater sensor network.*

Keywords: *underwater sensor network, UWSN, applications of UWSN, architecture of UWSNs.*

1. INTRODUCTION

THE GROWING interest in the design of underwater ad hoc networks is driven by the desire to provide autonomous support for many activities, such as monitoring of equipment (*e.g.*, underwater oil mining rigs) and natural events (*e.g.*, underwater seismic activity). Radio technology is unsuitable for underwater environments due to its poor propagation through water. As a result, acoustic modems are the current technology of choice for these scenarios [1]–[3]. Underwater protocol design has drawn the attention of the networking research community only very recently, and as a result little work exists in this area. While considerable work has been done at the physical layer [4]–[6] and in building devices [7], work at higher layers of the protocol stack is just beginning [1]–[3]. UWSNs are very different from ground-based existing networks due to the intrinsic properties of the underwater environments. They suffer from:

i. Large propagation delays: The propagation speed of acoustic signals in water is about 1.5 · 103 m/s, five orders of magnitude lower than the radio propagation speed (3.108 m/s) [7]. Consequently, the high resulting propagation delays will seriously damage localization and time synchronization [1].

ii. Node mobility: Underwater sensor networks move with water current (empirical observations suggest that water current moves at a speed of 3–6 km/h in a typical underwater condition [8]).

iii. High error probability of acoustic underwater channels: The underwater acoustic communication channel has a limited bandwidth capacity (of the order of KHz) that depends on transmission range and frequency, has variable delays and suffers high bit error rates, which are caused by noise, multi-path and Doppler spread. Consequently, temporary losses of connectivity can be experienced (shadow zones) [9].

Energy saving is a major concern in UWSNs because sensor nodes are powered by batteries and it could be difficult to replace or recharge batteries in aquatic environments. In acoustic networks the power required for transmitting is typically about 100 times more than the power required for receiving [9]. The design of robust, scalable and energy-efficient routing protocols in this type of networks is a fundamental research issue. Most existing data forwarding protocols proposed for ground-based sensor networks cannot be directly applied because they have been designed for stationary networks. The existing multi-hop ad hoc routing protocols are not adequate because they employ flooding techniques for packet routing (at least during the route discovery mechanism) that would lead an UWSN easily to energy exhaustion because in UWSNs the medium is highly variable and the routing overhead due to updates could be very high.

2. NETWORKING ARCHITECTURES FOR UNDER WATER SENSOR NETWORK

Fig. 1 illustrates the components of reference architecture for UWSNs. We can recognize some sensor nodes distributed over the ocean. They may be:

i. Fixed: The fixed sensor nodes may be distributed on the water surface with the aid of buoys or on the water bottom anchored to the ocean [8]; although they are fixed with tethers, they may move due to anchor drift or disturbance from external effects.

ii. Mobile: Mobile sensor nodes are more flexible and enable the autonomous auto configuration of these ad hoc networks in an arbitrary location.

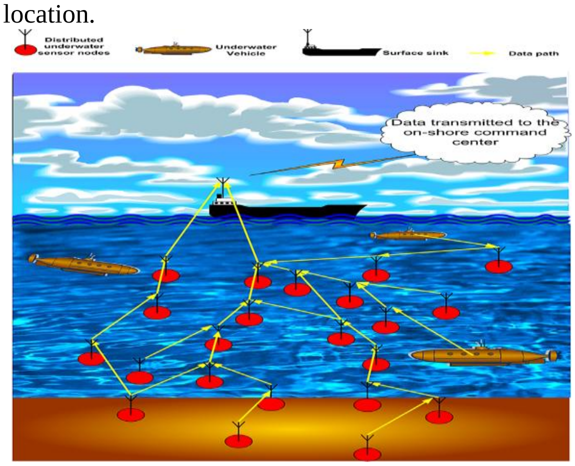

Figure 1: Underwater wireless sensor networks (UWSNs). [1]

All these sensor nodes communicate with each other using acoustic links and multi-hop routing; they relay data to the sinks via direct links or through multi-hop paths. The sinks may be:

i. Surface nodes (like the ship in Fig. 1): They can transmit data to the on-shore command center for example via radio or satellite.

ii. Underwater nodes: They can transmit data via multi-hop acoustic routes to a surface control center over the sea or to a surface station that retransmits them to the on-shore control center, for example via radio or satellite. The control center should collect and process the data received to extract conclusions. It is also possible that underwater sensors are able to communicate with a small number of autonomous underwater vehicles (AUVs) (see Fig. 1).

Based on this general description, some authors have classified UWSNs.

i. Static two-dimensional UWSNs for ocean bottom monitoring: They are constituted by sensor nodes that are anchored to the bottom of the ocean. They are interconnected to one or more underwater sinks by wireless acoustic links. These underwater sinks relay data from the ocean bottom network to a surface station. Typical applications may be environmental monitoring or monitoring of underwater plates in tectonics [9].

ii. Static three-dimensional UWSNs for ocean column monitoring: These include networks of sensors that float anchored at different depths. Typical applications are surveillance or monitoring of ocean phenomena (ocean bio-geochemical processes, water streams, pollution).

iii. Three-dimensional networks of autonomous underwater vehicles (AUVs): These networks include fixed portions composed of anchored sensors and mobile portions constituted by autonomous vehicles. Typical applications may be oceanography, environmental monitoring and underwater resource study.

In [4] the authors address ‘‘mobile’’ UWSNs instead of ‘‘static’’ and carry out the following classification:

• Mobile UWSNs for long-term non-time-critical aquatic monitoring:

These include networks of local underwater sensors that collect data and relay them to intermediate underwater sensors; these nodes forward the packets to the surface nodes, which transmit data, for example via radio, to the on-shore command center. Typical applications may be oceanography, marine biology, deep-sea archaeology, seismic predictions, pollution detection and oil/ gas field monitoring.

• Mobile UWSNs for short-term time-critical aquatic exploration:

These include networks of underwater sensors that collect data and forward them to the surface control center via multi-hop acoustic routes. Typical applications may be underwater natural resource discovery, hurricane disaster recovery, anti-submarine military mission and loss treasure discovery.

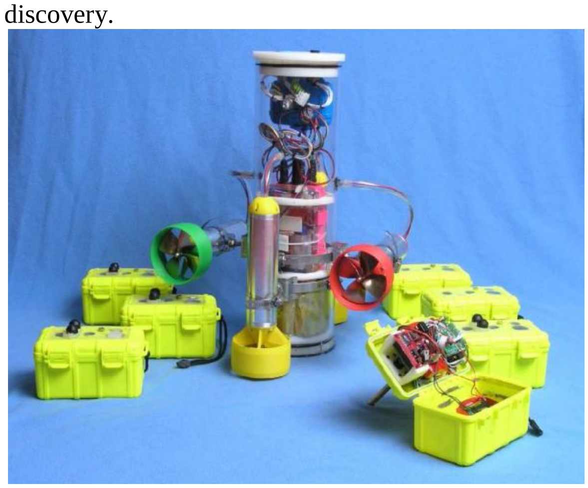

Figure 2: Group photo of the underwater sensor nodes. (a) the static sensor nodes (Aquaflecks) and a mobile node (Amour AUV) [4].

2.1 Underwater Sensor Node Aquafleck

We have built 20 underwater sensor nodes called Aquaflecks (see Figure 2). Each node is build around

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a CPU unit developed by CSIRO called a Fleck [5], based on the ATmega128 processor, with 128kbyte of program ash memory, 4kbyte of RAM, and 512kbyte of ash memory for data logging/storage. The Fleck is interfaced to a special optical communications board through 2 digital IO pins. One of these pins is used to turn an LED on or o_, while the other is used to sense the output from a matched photodiode. All the analog electronics (e.g., amplifiers etc) are on the interface board. The Fleck is also interfaced with a sensor board. The boards are connected in a stack using stack-through connectors. The underwater sensor node is contained in a yellow watertight Otter box that measures 170_100_90 mm and has been modified to incorporate the sensing and communication hardware. The Otter box is guaranteed to be watertight up to a depth of 30 meters. Each box has a high speed optical communication module that uses 532nm light, and is capable of a range of 2.2m/8m3, within a cone of 30 degrees and a maximum data rate of 320kbits/s. Additionally, there is a acoustic communication module using 30kHz FSK modulation with a range of 20m omni-directional, and a data rate of 50bit/s. The same module is also used for ranging4. For sensing, each node has a pressure sensor, temperature sensor, and a CMUCam camera capable of color pictures with a 255_143 resolution. The top side of the box contains a 170 mm rod with an LED beacon. The rod can be used by an AUV to locate the box, dock, and pick it up. Future versions will contain a XENON ash tube for increasing the distance for reliable node location to about 20 meters. The sensor node is powered by 3 alkaline C cells. Three C cells can provide 27 wh and four days of continuous operation with all sensors and communication hardware fully powered. The box is weighted to be 40% negatively buoyant, and balanced such that if dropped in water it always lands top up.

2.2 Amour AUV

In this project Amour is a mobile node AUV used to dock and transport the Aquafleck nodes. Amour can also locate an underwater sensor node and hover above it for data muling. Figure 2(Top) shows Amour next to Aquaflecks. The robot's body consists of an acrylic tube that is 48.26 cm long and 15.24 cm in diameter. It has four external thrusters with a maximum power of 150W and a maximum static thrust of 35 N each. The robot is statically balanced in an upright position. Two of its thrusters are aligned vertically. A pressure sensor provides depth feedback. A magnetic compass is used for orientation feedback and enables patterns of navigation, for example movement along a grid and spiral search. The power is provided by a 140Wh lithium polymer battery. The main processor is a 8-bit microcontroller with 64kbyte of program memory and 2kbyte of RAM. The bottom cap of the robot has a cone shaped cavity, designed for maximum mechanical reliability in docking and for optical communication. The robot can dock with sensor nodes in order to pick them up and transport them to a new location. This operation enables autonomous network deployment, reconfiguration, and retrieval. The docking system is general in that the robot can dock with any mate whose docking element is a 15.24 cm long rod of 1 cm diameter. The bottom cap also contains 4 light sensors pointing in complementary directions. The sensors can determine the direction toward a high frequency modulated light source (an LED) from up to 8 meters in clear water. A latching mechanism can hold the docked element with up to 200 N of force. Most of the electronics inside the robot, including the batteries, are placed in small Otter watertight cases. Recharging the batteries or reprogramming the robot can be done through watertight top cap connectors, without opening the main body.

3. APPLICATIONS

We see our approaches as applicable to a number of applications, including seismic monitoring, equipment monitoring and leak detection, and support for swarms underwater robots.

a) Seismic monitoring: A promising application for underwater sensor networks is seismic monitoring for oil extraction from underwater fields. Frequent seismic monitoring is of importance in oil extraction. Studies of variation in the reservoir over time are called "4-D seismic" and are useful for judging field performance and motivating intervention. Terrestrial oil fields can be frequently monitored, with fields typically being surveyed annually, or quarterly in some fields, and even daily or "continuously" in some gas storage facilities and permanently instrumented fields. However, monitoring of underwater oil fields is much more challenging, partly because seismic sensors are not currently permanently deployed in underwater fields. Instead, seismic monitoring of underwater fields typically involves a ship with a towed array of hydrophones as sensors and an air cannon as the actuator. Because such a study involves both large capital and operational costs (due to the ship and the crew), it is performed rarely, typically every 2–3 years. As a result, reservoir management approaches suitable for terrestrial fields cannot be easily applied to underwater fields.

b) Equipment Monitoring and Control: Underwater equipment monitoring is a second example application. Long-term equipment monitoring may be done with pre-installed infrastructure. However,

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temporary monitoring would benefit from low-power, wireless communication. Temporary monitoring is most useful when equipment is first deployed, to confirm successful deployment during initial operation, or when problems are detected. We are not considering node deployment and retrieval at this time, but possibilities include remote-operated or robotic vehicles or divers. Short-term equipment monitoring shares many requirements of long-term seismic monitoring, including the need for wireless (acoustic) communication, automatic configuration into a multihop network, localization (and hence time synchronization), and energy efficient operation. The main difference is a shift from bursty but infrequent sensing in seismic networks, to steady, frequent sensing for equipment monitoring. Once underwater equipment are connected with acoustic sensor networks, it becomes an easy task to remotely control and operate some equipment. Current remote operation relies on cables connecting to each piece of equipment. It has high cost in deployment and maintenance. In contrast, underwater acoustic networking is able to significantly reduce cost and provide much more flexibility.

c) Flocks of Underwater Robots: A third and very different application is supporting groups of underwater autonomous robots. Applications include coordinating adaptive sensing of chemical leaks or biological phenomena (for example, oil leaks or phytoplankton concentrations), and also equipment monitoring applications as described above. Communication for coordinated action is essential when operating groups of robots on land. Underwater robots today are typically either fully autonomous but largely unable to communicate and coordinate with each other during operations, or tethered, and therefore able to communicate, but limited in deployment depth and maneuverability.

d) Transmit Power: There is no fundamental limit to transmitter power, but it can have a major effect on the energy budget for the system. For energy efficiency and to minimize interference with neighboring transmitters we wish to use the smallest possible transmitter power.

e) Data Rate: This is a tradeoff between available power and channel bandwidth. Because acoustic communications are possible only over fairly limited bandwidths, we expect a fairly low data rate by comparison to most radios. We see a rate of currently 5kb/s and perhaps up to 20kb/s. In application such as robotic control, the ability to communicate *at all* (even at a low rate) is much more important than the ability to send large amounts of data quickly.

f) Noise Level: Noise levels in the ocean have a critical effect on sonar performance, and have been studied extensively. Ambient noise increases about 5dB as the wind strength doubles. Peak wind noise occurs around 500 Hz, and then decreases about -6dB per octave. At a frequency of 10,000 Hz the ambient noise spectral density is expected to range between 28 dB/Hz and 50 dB/Hz relative to 1 microPascal. This suggests the need for wide range control of transmitter power.

g) Signal Attenuation: Attenuation is due to a variety of factors. Both radio waves and acoustic waves experience 1=*R*2 attenuation due to spherical spreading. There are also absorptive losses caused by the transmission media. Unlike in-the-air RF, absorptive losses in underwater acoustics are significant, and very dependent on frequency. At 12.5kHz absorption it is 1dB/km or less. At 70kHz it can exceed 20dB/km. This places a practical upper limit on our carrier frequency at about 100kHz. There are additional loss effects, mostly associated with scattering, refraction and reflections. A major difference between RF and acoustic propagation is the velocity of propagation. Radio waves travel at the speed of light. The speed of sound in water is around 1500 m/s, and it varies significantly with temperature, density and salinity, causing acoustic waves to travel on curved paths. This can create silent zones where the transmitter is inaudible. There are also losses caused by multipath reflections from the surface, obstacles, the bottom, and temperature variations in the water and scattering from reflections off a potentially rough ocean surface.

h) Proposed Acoustic Communications Design: Many of these forms of loss are unique to acoustic communications at *longer* distances. In particular, multipath reflections, temperature variation, and surface scattering are all exaggerated by distance. Inspired by the benefits of short range RF communication in sensor networks, we seek to exploit *short-range underwater acoustics* where our only significant losses are spreading and absorption. We are developing a multi-hop acoustic network targeting communication distances of 50-500 meters. Using a simple FSK signaling scheme we anticipate sending 5kb/s over a range of 500m using a 30 mW transmitter output. The primary limitation is set by spreading loss and the background noise of the ocean.

4. HARDWARE FOR UNDERWATER ACOUSTIC COMMUNICATIONS

Acoustic communications is a very promising method of wireless communication underwater. At the hardware level, underwater acoustic communication differs from in-the-air RF in a few key ways. In both systems we transmit a tone or carrier, which carries the data through modulation, such as amplitude, frequency or phase modulation. The primary differences between modulation techniques lies in the complexity of the receiver, the bandwidth required, and the minimum acceptable received signal-to-noise ratio (SNR).

5. CONCLUSION

In this paper, we have studied networking architecture of underwater sensor network, its applications and hardware for acoustic communications. We have also studied that routing in underwater is different from MANT and WSN so the protocols of MANET and WSS will not work in UWSN. So, designing energy-efficient routing protocols for this type of networks is essential and challenging because sensor nodes are powered by batteries, which are difficult to replace or recharge, and because underwater communications are severely affected by network dynamics, large propagation delays and high error probability of acoustic channels.

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