Autonomous Wireless Lake Monitoring

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Underwater sensor networks (USNs) are an emerging research field, with applications ranging from military to environment monitoring. The authors present an innovative USN application: autonomous wireless lake monitoring. Such technology can be applied to monitor lakes, especially for limnology, where scientists determine water quality by measuring environmental variables such as temperature, pH, and dissolved oxygen. This application, which can collect and analyzes those physical quantities in near real time, could help improve quality of life for humans and prevent ecodisasters.

Underwater sensor networks (USNs) are an emerging research and technology field with the potential for many innovative applications.[1] Underwater wireless communications allow us to develop new applications such as pollution and environmental monitoring, disaster prevention, and scientific sampling from fresh water and salt water.

Lake and reservoir monitoring is one of the most important fields to use USN technologies. Most water consumed by human beings comes from fresh water reservoirs such as lakes. They are also important for commercial purposes, such as in aquaculture, which requires animal and plant populations under controlled conditions. Finally, lakes present a delicate ecosystem made up of the physical, chemical, and biological properties contained within these water bodies. In this context, many variables are important to determine the water quality, such as temperature, pH, and dissolved oxygen. By measuring those physical quantities in near real time, we can improve human quality of life.

In this article, we present an autonomous wireless lake monitoring system. We show all system architecture, including sensor node architecture, network topology, and communications. Our system is composed of underwater sensor nodes that sense the environment, process data, and communicate among themselves. The sensed data is routed by sensor nodes and propagated through the network to reach a gateway, where it is sent and made available on the Internet. Data can be stored in a database system and retrieved via web by users and scientists.

LAKE MONITORING

Current lake monitoring solutions require human intervention and the use of specific in-local sensors. They are not autonomous, do not allow preprogrammed tasks, and require a specialist to operate them almost all the time. Sensors have to be manually positioned, and the values are read by a human or stored in datalogger equipment, thus only available for evaluation later.

Measurements at different depths in a lake take a long time and are error prone. For instance, to perform measurements in a lake, sensors are connected to a base station with a cable. This cable contains depth marks that should be visually inspected to retrieve the actual sensor depth. A human operator sinks the sensor into the lake and isopycnal measurements are made, taking into account the cable marks. If the operator misses one of these cable marks, all measurements might be wrong. Furthermore, time is crucial for ecosystems. For example, determining variations in oxygen can avoid fish death and ecodisasters.

Commercial applications of USNs can help aquaculture to enhance production. Aquaculture is the use of aquatic environment to farm aquatic organisms such as fish, crustaceans, and aquatic plants. In lakes, aquaculture involves cultivating freshwater populations under controlled conditions. Monitoring those conditions is essential for population growth and economic profit.

Ecology and environmental science also need USN support. For instance, in limnology, researchers are interested in studying, managing, and conserving aquatic ecosystems. For them, it is of fundamental importance to sense the environment and collect the sensed data. Current systems require human intervention, usually, a group of scientist usng local equipment to collect sensor values.

Recently, some architectures have been developed based on research activities in underwater wireless networks. Most of them focus on oceans. For example, Jun-Hong and colleagues[2] proposed a testbed for ocean monitoring. Telemonitoring for underwater monitoring using the cloud to store data has recently been proposed.[3] Wireless and autonomous systems for lake monitoring are a new application that has many benefits. Hydroelectric reservoirs[4] can also benefit from these systems.

UNDERWATER LAKE MONITORING ARCHITECTURE

The key challenge when monitoring a lake environment is to replace costly manual measurements and perform a remote supervised control. In most cases, lakes do not have any communication infrastructure. To overcome these issues, as shown in Figure 1, we propose an autonomous wireless system in which platforms float at the lake surface and host one or more sensor nodes. Each of these sensor nodes have processing, sensing, and communication capabilities.

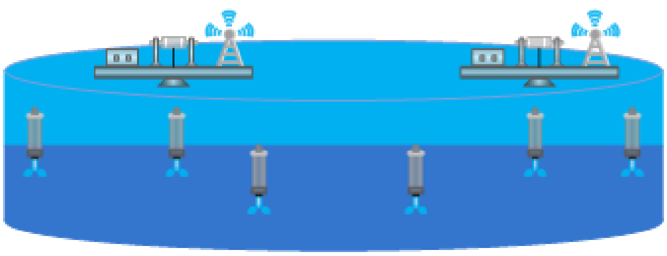

Figure 1: Overall system architecture.

Figure 2 presents a detailed view of the lake monitoring system network. At least one platform acts as a gateway, interfacing the Internet and the underwater wireless network. For example, the gateway receives any incoming messages from the Internet as remote supervised control messages and then sends the messages to the sensor nodes. The sensor nodes and gateway form an ad hoc underwater network. All messages exchanged between sensor nodes and gateway are routed through this dynamic network.

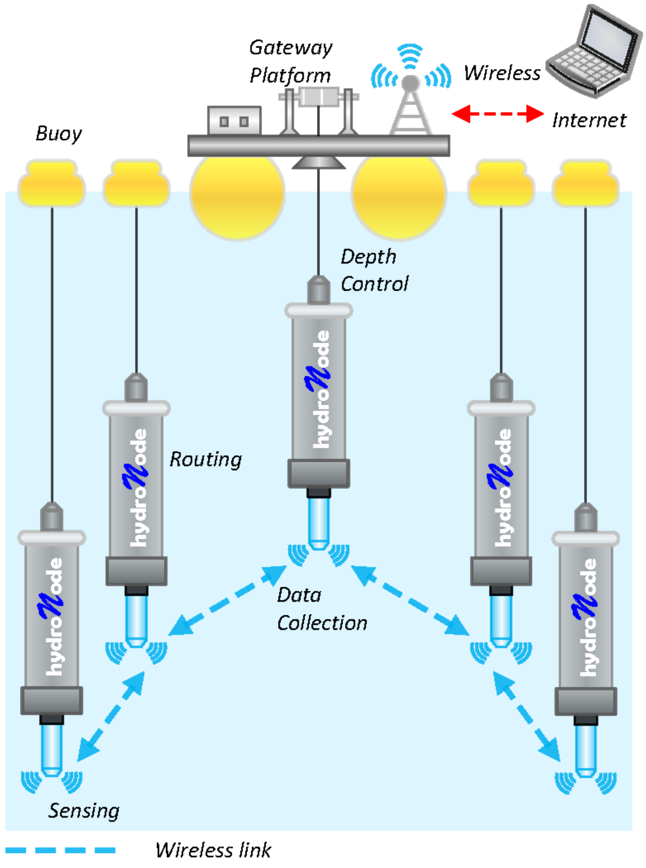

Figure 2: Detailed network system.

Sensor nodes can also be tied to buoys, where they can be easily retrieved without getting lost and polluting the environment. The platform can be accessed with any wireless technology, such as GPSR, 3G, LTE, and satellite for remote locations and Zigbee or Wi-Fi for nearby regions. Sensor nodes can also be attached to a special platform. This platform enables the capability to remotely deploy sensor on different layers of the lake. More precisely, as shown in Figure 2, sensor nodes are attached to the platform via a cable. The platform contains a motor that controls the sensor node depth. A potentiometer on the platform is used to precisely determine the depth with less than 1-cm error. There is no doubt that depth control is important for taking measurements in the water columns. For instance, scientists are interested in understanding lake stratification.[5] Depending on the event being monitored, the sensor nodes can move vertically and be placed elsewhere.

Sensor Nodes

The sensor nodes perform many tasks in the network, including sensing, signal processing, communication, and routing. Figure 3 illustrates a general underwater sensor node architecture. Sensor nodes have a power supply and energy management unit, processing unit, depth control, communication unit, and sensing unit. For more details on underwater sensor nodes, Viana and colleagues[6] present a survey that aids in the development of underwater sensor nodes.

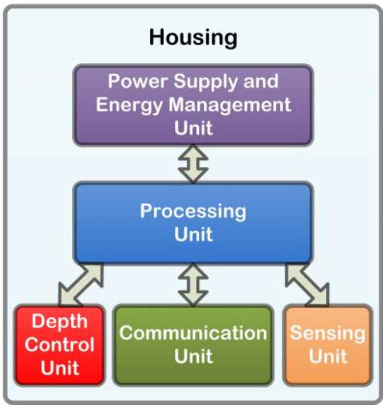

Figure 3: General underwater sensor node architecture.

Sensors allow physical values measurement. For example, a sensor can measure water temperature, pH, or dissolved oxygen. As previously described, sensor nodes have wireless communication capabilities, allowing network configuration and application development. While sensors capture metrics, sensor nodes also act as routers, allowing the sensor data to reach a gateway. Once the gateway receives data, one can remotely access this information through the Internet.

Figure 4 presents the platform operating in water. It has a motor and a cable controlling the node's depth. It uses Hydronode[7] as the underwater sensor node, which can be used in the lake monitoring application. The boards and microprocessors for processing the signal and network messages are located internally. Externally connected are the commercial sensors used for sensing, as the temperature sensor in the figure, and acoustic (or optical) modems used for wireless communication.

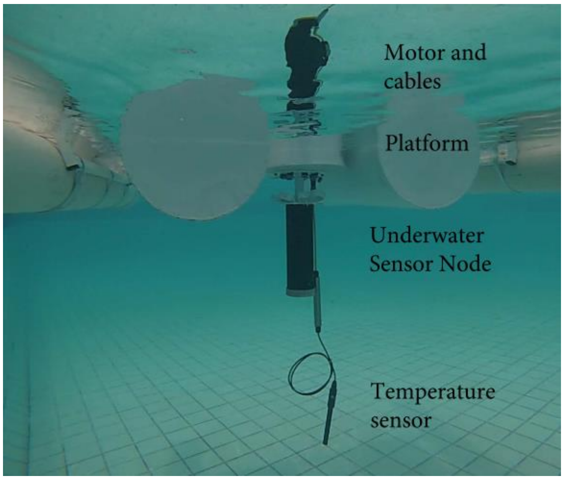

Figure 4: Underwater sensor node operating with a platform.

Sensors

The main sensors used for the wireless lake monitoring application are *pH*, *electrical conductivity*, *dissolved oxygen*, *temperature*, and *turbidity*.

pH is the measure of hydrogen ions in a solution. It is especially important to measure pH in aquatic environments because it is an indicative of algal blooms, nutrient deficiencies, and metal toxicities in water, all of which can damage aquatic life.

Electrical conductivity measurement determines the concentration of ions in water solutions. High values of this parameter can be indicative of contaminants. Hence, it is used as a parameter to determine purity and quality of water.

Dissolved oxygen or oxygen saturation is a measurement of how much noncompound oxygen is dissolved in water.[8] It is an important parameter in assessing water quality because of its influence on the organisms living within a body of water. Aquatic fauna need adequate dissolved oxygen levels to survive. Dissolved oxygen is necessary to many forms of life including fish, invertebrates, bacteria, and plants. These organisms use oxygen in respiration. It is also pivotal to the sustainability of entire water ecosystems. Low levels of dissolved oxygen, called deoxygenation, are responsible for the growth of anaerobic bacteria and algae that results in massive fish death. A high level of dissolved oxygen can harm aquatic life too. Consequently, dissolved oxygen is one of the most common indicators of water quality, and is fundamental in monitoring aquatic environments. Different species have different dissolved oxygen requirements. As soon as one observes that the oxygen level is dropping below the species survival threshold, one can move the species to a different location or add oxygen, saving their lives. Adequate temperature is vital for all forms of life. It determines what kinds of organisms will proliferate in the environment. Therefore, monitoring temperature allows for modeling the population dynamics of rivers, lakes, and oceans.

Turbidity is the measurement of how much the particulate matter suspended causes light to scatter in water. It is very important to monitor turbidity levels, because the vegetation that grows in water is affected by the amount of light it receives. Thus, altering the natural turbidity of a water stream can alter its whole ecosystem.

CHALLENGES OF NETWORK PROTOCOLS AND SERVICES FOR USNS

In most cases, USNs rely on acoustic channels characterized by long propagation delays, low communication bandwidth, high channel error rates, link asymmetry and anisotropy, and temporo-spatial multilevel dynamics.[2] These issues are challenging, especially in terms of the physical, medium access, and network layers design.

Figure 5 shows the first three network layers. It follows the TCP/IP architecture. Each sensor node acts on the three layers: physical layer (PHY), data link layer (LNK) and network layer (NET).

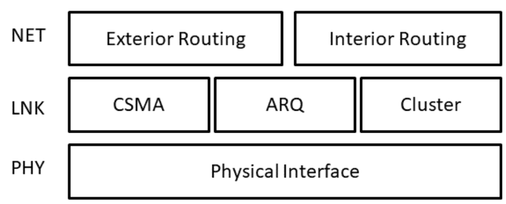

Figure 5: Network layers.

Signal transmission and reception happen at the physical layer. As previously discussed, acoustic or optical modems could be used for wireless communication. Acoustic modems have a higher range and do not depend on the medium's turbidity, unlike optical modems. In Figure 5, the physical layer depends on the physical interface being used.

The data link layer must provide frame communication and avoid medium contention. The MAC sublayer should consider multiple nodes competing for the communication medium. Multiplexing techniques, such as TDMA, CDMA, SDMA and CSMA, could be used; each has its benefits and disadvantages in wireless underwater communication. Several MAC protocols have been proposed in the literature for underwater sensor networks.

Recently, underwater MAC protocols were tested in real sea experiments.[9] In this work, the authors pointed out several issues that have not been well studied in underwater networks, such as heterogeneous packet delivery, multihop interference, and spatial and temporal communication range uncertainty. They compared three protocols: random-access-based UW-Aloha, handshaking based SASHA (selective Arq with slotted handshaking-based access), and scheduling-based PMAC (pipelined transmission MAC).[10] According to their work, PMAC presented better end-to-end throughput and end-to-end delivery ratio, achieving an end-to-end throughput of 25 bps. Figure 5 summarizes the main data link protocols. CSMA-based protocols (and Aloha based on random access), ARQ-based protocols (such as SASHA), and cluster-based protocols (such as PMAC) are all data link protocols that fit the application requirement.

To secure data communication, one might use encryption. A mechanism that provides end-to-end authentication in underwater networks[11] could be used, guaranteeing integrity and authentication.

Routing happens at the network layer. Figure 5 shows the presence of two types of routing protocols, exterior routing used to reach devices outside the network and interior routing used for reaching computing elements inside the network.

The platform acts as a gateway and performs the exterior routing. For instance, traditional IP messages can be routed from/to the Internet to/from the platforms running IP.

Nodes can use interior routing inside the network to reach any sensor node or platform. Research for routing in USNs has produced many multihop routing protocols. Pressure routing,[12] depth-based routing,[13] opportunistic routing,[14,15] and dynamic source routing[16] are examples of routing protocols that can be used in the application.

Without loss of generality, more than one platform can act as a gateway. Thus, an anycasting protocol can be used for sensor node messages to reach at least one of the gateways (such as plasma routing[17]).

The application does not impose a specific physical link, data link, or network protocol. For the lake monitoring application, there are two main functionalities: data collection and data dissemination.

A data collection protocol is used to collect the sensed data from each sensor node. Current sensors value can be stored in 10 bits. Five sensors are presented in each sensor node, summing to 50 bits per sensor node. A data dissemination protocol (such as CodeDrip[18]) is necessary for reconfiguration, time synchronization dissemination, and sensor node management.

The network must provide two services for the application: localization and time synchronization. The sensed data must have the time and the location it was sensed. Many solutions exist for localization and time synchronization in USNs. One localization mechanism that does not require messages exchange is to have GPS on the platforms or buoys, learning the surface coordinates. GPS does not work underwater, but the depth can be obtained from a pressure sensor. For time synchronization, the platforms can periodically synchronize with the sensor nodes using a dissemination protocol. To reduce messages exchanges, the offset and clock drift could be learned and used to correct the clock.

Energy consumption is also relevant. To save energy, green protocols could be used. Recently, Coutinho and colleagues[19] described green protocols for various layers for USNs.

ADVANTAGES

Autonomous wireless lake monitoring has many advantages:

- *Nonhuman intervention*. The autonomous wireless network can operate without human intervention. This can save time, money, and lives.
- *Programmable tasks*. The monitoring task can be predefined. For instance, the platform can be preprogrammed to take measurements at different depths, allowing a better understanding of the lake stratification. It also reduces cost, as it does not need human presence.
- *Low cost*. The system can reduce the number of people involved in the monitoring. Human presence and actuation are not necessary after setup. Furthermore, it can also reduce equipment cost. Usually boats are rented by the hour to take measurements. Professionals, such as boat drivers and life guards, might also be required.
- *Near real time*. The system allows monitoring in near real time. Current studies have to deploy sensors and wait for them to be collected, or wait for the person using dataloggers to return to the laboratory with the collect data. Sensed data can be available on the Internet almost instantaneously.
- *Faster intervention*. Because the monitoring is happening at almost real time, one ca act on the sensed data faster. For instance, when detecting a fast drop on the oxygen level, aquatic life can be transported to other regions or oxygen level can be increased (for example, use oxygen tanks), saving lives.
- *Manageable*. The network and the sensor nodes can be more easily managed. From remote locales, it is possible to manage the status of the network and its elements.
- *Data logs*. Data can be stored in logs that can be accessed via the Internet. A human reading the values might misread them or lose the information. For instance, a notebook with the measured values can get wet. Or the dataloggers might have their memory card malfunction or damaged. If data are transmitted over the Internet, the malfunctioning of memory cards will not affect the collection of measurements.
- *Remote access*. Scientist can access the sensed data from remote places. This can also lead to faster intervention.
- *Robust*. When using cable sensors, if a cable breaks, the whole system stops working. Wireless networks add robustness to the network by allowing some cables or wireless links to break and still collect the data.
- *Low maintenance*. When operating, the system requires low maintenance.
- *Larger spatial analysis*. More sensor nodes can be used to make measurements. Each of them works independently, without requiring more people to make more measurements. Therefore, more samplings can be taken at the same time at different locations.
- *Simultaneous measurements*. Because more nodes can be deployed, they can take measurements at the same time. In current systems that use human intervention, each person is usually responsible for one sensor.
- *Less error in depth measurements*. Because the nodes are positioned via cable and there is a potentiometer that measures their positions, its depth is less error prone than having a human being counting marks in a cable.

EXPERIMENTS AND RESULTS

To validate our proposed system we performed a series of experiments. First, we tested the system in a controlled environment, so that the results could be analyzed and validated. In the controlled environment, we controlled the temperature of the water by measuring the temperature with laboratory equipment and added ice to the water to cool it down. We added ice to the water in two steps. Figure 6 shows the temperature measurements done by the sensor node over time.

As expected, it agreed with the laboratory measurements. In the two moments that ice is added to the water, it cools down the water and our temperature sensor reads it. It is possible to detect the moments we added ice to the water by looking at the temperature drops. First the temperature drops from almost 24°C to near 22°C. After the water temperature stabilizes, we added icy again and the temperature dropped from 22°C to near 18°C.

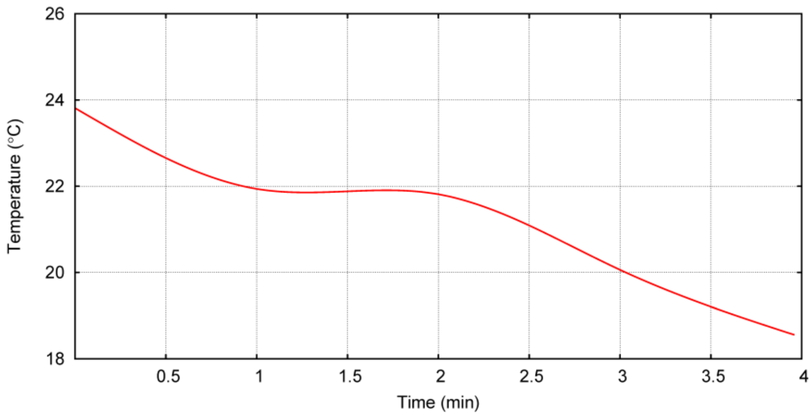

Figure 6: Temperature measurements in a controlled environment where ice was added twice.

We also investigated the energy consumption while using depth control. We let the platform move the sensor to certain depths and measured the current consumption. We used a 24-V power supply. Two 12-V car batteries are enough for that. The left panel of Figure 7 shows the peak current and the right panel shows the average current while moving the sensor to the distance displayed in the *x*-axis. The peak current happens when the motor starts running. The average current considers the whole movement. As observed, the current consumption does not increase linearly. The platform motor pulls faster for longer displacements and consumes less per meter for larger movements. Another observation is that rolling (going upward) the cable carrying the sensor node consumes more than unrolling (going downward). This is also expected as going upward is against gravity and downward is favorable by gravity.

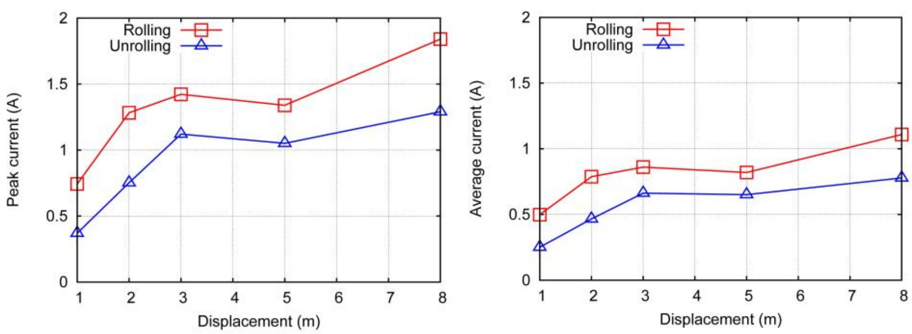

Figure 7: Energy consumption for depth control. Left: Peak current while moving the sensor. Right: Average current while moving the sensor.

Finally, we analyzed the human intervention. We considered the number of times a human would need to operate to read the sensors values every 5 minutes. Figure 8 shows the benefit of an autonomous system. An operator can schedule the reading events once while without it a human would need to read the values periodically. Due to the huge gains, the plot is in logscale.

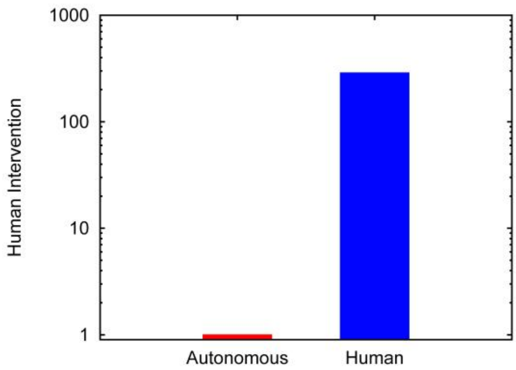

Figure 8: Number of times a human intervention is necessary.

FINAL REMARKS

Advancements in many areas have enabled the development of USNs. These networks composed of underwater sensor nodes with communication capabilities can be used for many applications. In this article, we described a complete solution for one application: autonomous wireless lake monitoring.

Future work will investigate scientific topics related to the system, such as node and platform positing. It will also involve using it with other areas of science, such as biology, and other applications, such as monitoring hydroelectric reservoirs and oil pipelines. We also plan to explore big data techniques.

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