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Survey on the design of underwater sensor nodes

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Abstract Underwater wireless sensor networks are networks composed of various underwater sensor nodes (USNs) that are able to communicate with each other. The vast majority of Earth's surface is composed of water, which makes such networks a very interesting research topic and enables a variety of applications, i.e, from oil monitoring to real time water pollution control. The design of USNs is paramount to the network's operation. In comparison to terrestrial wireless sensor nodes, USNs are more expensive, larger, and present greater energy consumption, due to the harsh conditions of the aquatic environment. This leads to different challenges that need to be addressed in the design of the node, including processing, communications, energy management, data sensing, and storage. This survey aids in the development of underwater sensor nodes, and underwater applications. We present a general architecture of USNs and discuss the basic functions that must be accomplished by each unit. We also present a comprehensive study of all elements that compose a sensor node, including microcontrollers, memories, sensors, and batteries. In doing so, we highlight which aspects should be of pivotal importance in the design of a USN and how they affect communication protocols and applications. We believe that this survey can facilitate and guide development of future UWSN applications and protocols.

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1 Introduction

Underwater sensor network (UWSN) is an important research area that is attracting increasing interest from both the research community and the industry. Oceans, rivers and lakes are critical to the life on our planet and monitoring these environments is a hard and costly task [29]. Thus, there is a large number of applications where UWSNs are important, such as ecosystem preservation, disaster prevention, oil/gas exploration, and freshwater reservoirs management [30].

In oceanography, for example, UWSNs can perform sampling of the coastal relief as a way of obtaining information to infer and predict specific characteristics of the environment. Data collected can also be used to avoid possible risks to navigation. Moreover, in military, UWSNs may be applied to identify submarines, helping to prevent possible attacks. UWSNs can also benefit the industrial area by helping in the control and monitoring of undersea pipes and fishing machinery.

An underwater sensor network is formed by many autonomous sensor nodes. To accomplish the goals of a given specific underwater application and develop an UWSN, one must design an underwater sensor node (USN). Basically, an USN can sense the environment, collect data, process and transmit them.

One of the main challenges of deploying such a network is the sensor node development, including its high cost when compared to terrestrial sensor nodes [20]. Most USN hardware architectures are aimed at very specific applications, lacking in generality. Also, researchers are in need of a unified platform to test practical performance of network protocols. This is evident from recent efforts in the research community for platforms to promote experiments in UWSN [19,40,60].

In this paper, our main contributions are the following:

- We present a survey on the design of underwater sensor nodes, which can aid in the development of sensor nodes, communication protocols and innovative applications. Our main objective is to help the research in the underwater sensor networks area, providing valuable information to researchers that are planning to construct an USN.
- We propose a general architecture of USNs, built up of interchangeable modules that perform the following functions: power supply and energy management, depth control, communications, sensing and processing. This general architecture can serve as a model for many UWSNs applications and protocols, and for classifying and understanding the current technology and its implication.
- We show that sensor nodes can be built using only off-the-shelf components, greatly reducing total cost.
- We present an extended list of sensors and other USN devices, which can be selected accordingly to the specific application.
- Besides hardware and device description, we show a description of current battery technologies, and how its choice affects the node's design.

We hope that this survey can facilitate and guide development of future UWSN applications.

This paper is organized as follows. In Sect. 2, we discuss characteristics and requirements of USNs, including sensed parameters, data acquisition, processing, storage and communications. In Sect. 3, we present a general architecture of USNs. In Sect. 4, the devices used in the processing unit are compared, such as microcontrollers and memories. Section 5 discusses the main sensed parameters in the aquatic environment, listing the commercial and academic available sensors and their potential applications. Section 6 treats in greater detail the challenges of power supply and energy management of USNs. Depth control units are discussed in Sect. 7. Housing materials are treated in Sect. 8. Finally, we summarize our contributions and conclude this paper in Sect. 9.

2 Challenges and requirements

Underwater sensor nodes are compact, autonomous devices that compose underwater sensor networks. These devices have three major functions: to sense and collect data from its environment; to process the collected data; to communicate with other underwater sensor nodes or gateways.

In comparison to terrestrial wireless sensor nodes, USNs are more expensive, larger, and present greater energy consumption, due to the harsh conditions of the aquatic environment.

Designs of these devices have to cope with a variety of requirements and challenges proper of underwater wireless communications and aquatic environment conditions, which we enlist in the following.

2.1 Energy efficiency

The UWSNs operate as long as the underwater nodes stay active. Hence, designing sensor nodes that are energy efficient is one of the most important tasks for network operation.

Usually, sensor nodes are powered only by their own batteries, without external power supply. Due to the high number of nodes and large deployment ranges in UWSNs, it is very difficult to recharge all the nodes. Thus, one should be concerned in designing hardware and software as energy efficient as possible. All these facts make energy efficiency one of the top priorities in USN design.

2.2 Low cost

Actual UWSNs should be composed of hundreds to thousands of nodes, in order to achieve high spatial data resolution. However, as pointed out in [41], underwater acoustic communication today are typically expensive—US$10k or more.

The aquatic environment also imposes higher requirements considering housing, what makes total cost even higher. Therefore, building low cost USNs is a big challenge in the construction of underwater nodes and networks, guiding development of node's design.

2.3 Spatial deployment

Nodes must be spatially deployed in a way that enables efficient communication and accurate measurements. Nevertheless, obstacles and variations of data link quality with time can result in loss of links. In this case, certain regions can become invisible for the network, which should be avoided.

2.4 Underwater communications

Sensor nodes must be able to communicate underwater, in order to send collected data to a station that will analyze them. Still, as water imposes several difficulties for communications, this is not easy to achieve. Accordingly, design of USNs is highly driven by the need to provide reliable communications.

2.5 Multi-hop architectures

In long rang deployments, an USN may not be able to reach the sink node, or gateway, in the network. This causes the need for a multi-hop architecture, in which nodes communicate not only with a base station, but also with other nodes. Albeit multi-hop architectures resolve range concerns, new challenges arise, such as the need for efficient routing and MAC protocols. For example, Slotted Aloha at its best performance can achieve only 18 % of channel utilization [63]. Thus, USNs must consider hardware and software support for those protocols.

2.6 Aquatic environment conditions

Unlike terrestrial sensor networks, UWSNs have to overcome challenges as pressure and turbidity, which affect not only communications, but also data collection and the node's housing. Hence, it is necessary that the node and sensors are tight, which requires special considerations in the housing's design.

Also, because of effects such as multipath and latency, communications in the aquatic environment typically present high transmission errors and low data rates. Therefore, USNs must be designed to support network protocols that can achieve robustness and overall performance. It is clear that energy consumption, processing time, and the current state of the art communication are all relevant in the design of an USN.

3 Underwater sensor node architectures

3.1 A general model for underwater sensor node architectures

Despite many possible architecture models, underwater sensor nodes present functions that can be grouped in specific units. Hence, we here propose a general architecture for underwater sensor nodes, depicted in Fig. 1. In this architecture, a USN is composed of five main units:

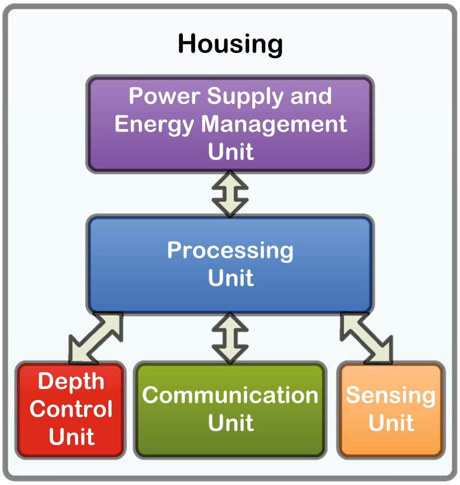

Fig. 1 General underwater sensor node architecture

processing unit; communication unit; sensing unit; power supply and energy management unit; depth control unit.

The processing unit is the central part of an USN. It coordinates all other units operations, enabling the execution of algorithms, data sampling and storage, as well as communications to other devices. One of the main challenges in choosing hardware parts is to balance processing power with low energy consumption demands, which often configures a trade-off between these two requisites.

The sensing unit is composed of a group of sensors. The sensors can be classified in two primary ways: analog and digital sensors. While analog ones convert electrical signals related to change in physical conditions [65], digital sensors produce a digital output stream. In turn, this stream can be read via a diverse range of protocols such as SDI12 and HART. There are many types of sensors, and choosing the ones that will compose the USN sensing unit is guided mainly by the application requirements.

The communication unit is the underwater sensor node's module responsible for handling communications. Because of the harsh conditions of the aquatic environment, its components must be specially designed, so to be able to establish communications in an energy efficient way. With these components, it is possible to establish point to point communication between nodes. Then, with various nodes, one can constitute a multi-hop network.

The power supply and energy management unit must provide the node with a reliable energy source, as well as control energy consumption. In doing so, it is fundamental to know of the battery state of charge (SOC). This is commonly accomplished using charge estimators. Based on this information, the unit can schedule the USN operation and inform when a node is about to be out of energy, in order to facilitate the UWSN reconfiguration.

The depth control unit sets the depth in which the node operates. The water conditions (ex: temperature, salinity, etc.) vary greatly with depth, so it is desired to measure these water characteristics along a water column. If all the nodes are equipped with this module, then the depth of each individual node of the UWSN can be controlled, enabling a more complete understanding of the environment or even network topology control.

Although not a part of the USN architecture, one of the most important factors in the design of the node is the housing. The housing guarantees that the node can be deployed underwater, offering tightness and mechanical support for the sensors.

3.2 Current architectures

The general model proposed in the previous section can be used for classifying and understanding the current technology, as nowadays many different sensor nodes are used for monitoring water.

Depending on the application requirements, the sensor node is built in different forms. For example, current ocean measurements use ARGO [61]. It combines sensing, processing, depth control, and power supply and energy management units. However, it does not possess a communication unit because communications are held out of water via satellite.

Another example is HydroNode [50], used in lakes and rivers. It combines all units described in the general architecture model, except for the depth control unit, which is currently not present in the node.

The autonomous underwater explorer (AUE) is a spherical sensor node, built to monitor ocean currents [42]. It encompasses all of the units described earlier. Also, its communication unit includes a GPS with the purpose of self localization of each node. Current sensor node technologies are shown in Fig. 2.

We take a deeper look into each unit in the next sections.

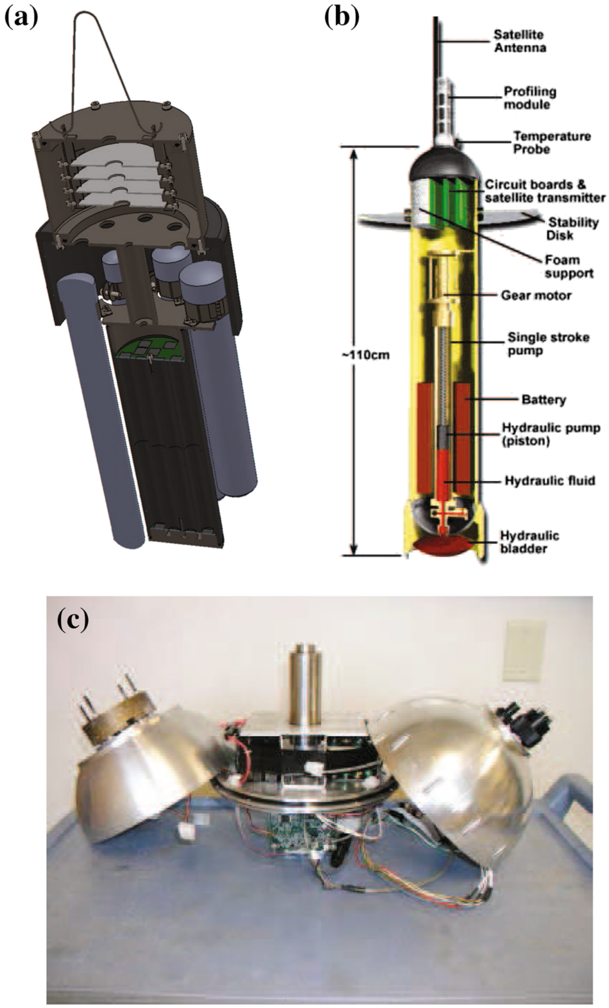

Fig. 2 Examples of underwater sensor nodes. **a** HydroNode. Image from [64]. **b** ARGO. Image from [61]. **c** AUE. Image form [42]

4 Processing unit

In a basic setting, processing units have four modules (which can be placed together in a single integrated circuit): processor, memory, analog-to-digital converters (ADCs) and digital interfaces. Next we present some off-the-shelf components that are commonly used in these modules. Figure 3 depicts the processing unit modules that are detailed next.

4.1 Microcontrollers

Microcontrollers (MCs) are integrated circuits that contain a processor, memory and peripherals. Common peripherals include: digital interfaces; ADCs; comparators; timers. These peripherals make microcontrollers best suited to the design of embedded systems like USN

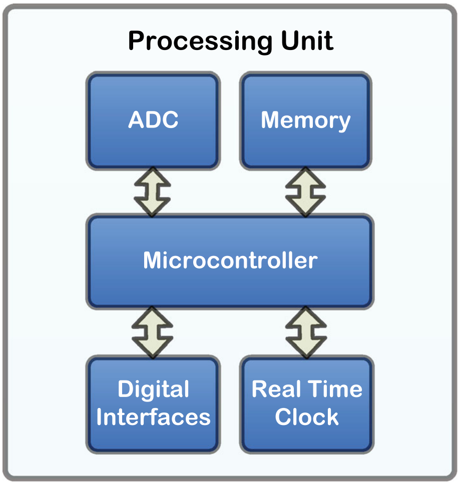

Fig. 3 Processing unit modules block diagram

because they enable interfacing with sensors, actuators and modems. There is a great variety of MC types, each one with different power consumption and peripherals. Table 1 compares off-the-shelf microcontrollers.

When choosing a microcontroller to be part of the processing unit's design, several characteristics must be accounted for. To begin with, low power consumption is one of the most important. Because the efficiency of a UWSN rely on the number of active links, USNs must remain operational for long periods of time. Thus, they need to have little energy consumption, leading to the use of low power microcontrollers in their designs.

In order to save energy, microcontrollers typically present one or more low power modes, in which functions are disabled and clock is reduced. The most common power modes are: power active, power idle and power down. Power active mode enables all hardware parts, but also consumes the most power. It is used to perform operations such as calculations, where high processing is needed.

In the power idle mode, most peripherals are disabled and a reduced clock is used. This mode is sufficient to handle some interruptions.

The power down mode typically activates only RAM retention. In both power idle and power down modes, the devices is waken either by software or hardware interruptions. One example of such interruptions is the reception of data from the network.

It must be noted that, while power active mode presents the highest power consumption, it operates for only fractions of time. In most of the time, low power modes such as power idle and power down mode are used [21]. So, in choosing a low power microcontroller to build a USN, one must not only account for the power active mode consumption, but also for the consumption of the other power modes.

The number of instruction bits of modern MCs range typically from 8 to 32 bits. While 4 bits devices still exist and are commercially available, they are obsolete in more complex designs, consuming more instructions to execute tasks. By far, the most common low power microcontrollers are 8 bits. Nevertheless, 16 bits and 32 bits models are also present, and their use is growing.

Other factors to be considered in the choice of a microcontroller include: number of general purpose I/O pins; memory; ADCs, digital interfaces. In the next sections, we take a deeper look in each of these topics.

Table 1 Microcontrollers comparison

Manufacturer/model	Bits	RAM	Power active (mA)	Power idle (μ A)	ADC ports	ADC resolution	Digital interfaces
Freescale MC9S08LL36 [4]	8	4 kB	2	0.65	10	12	USART, SPI/I^2C
Texas Instruments MSP430F2274 [14]	16	4 kB	0.27	0.3	12	10	UART, SPI/I^2C, IrDA
Microchip PIC18F14K22 [5]	8	4 kB	0.15	2.3	12	10	USART, SPI/I^2C
ST Electronics STM8L151R6 [6]	8	4 kB	0.195	0.35	28	12	USART, SPI/I^2C, IrDA
Silicon Labs C8051F960 [10]	8	8 kB	2.2	0.7	16	12	USART, SPI/I^2C
EM Microelectronic EM6819 [13]	8	512 B	0.14	–	8	10	SPI
Analog Devices ADUCM360 [8]	32	8 kB	3	1	12	24	UART, SPI/I^2C

Table 2 Memory comparison

Memory	Size	Life
EEPROM [54]	128 bits–2 Gbits	1–10,000,000 rewriting operations
Flash [46,48]	16 Kbits–512 Gbits	100–1,000,000 erasing operations

Computer on chips modules (e.g. Gumstix, Raspberry Pi) could be incorporated inside the sensor nodes to provide reconfigurable features to the currently available modems. The drawback is their energy consumption.

4.2 Memory

Memories are primarily classified in two ways: volatile and non-volatile memories.

The more recognizable use of volatile memories is RAM, which is pivotal to microcontroller's functioning. As such, the number of RAM bytes of a MC must be chosen in a way that permits the correct execution of programs, without compromising the USN operation. A common number is 4 kB RAM, which is present in many commercial microcontrollers and is good for most applications. However, if implemented protocols need high memory, such as routing protocols that store lots of information in the form of routing tables, this number should be analyzed in a more detailed way.

Non-volatile memories are primarily used for code and data storage. Low power microcontrollers have non-volatile memory values ranging from 16 to 128 kB, used for code storage. However, this memory can not be used for data storage—there is an information memory for this purpose, but is typically only a few bytes.

In these cases, external memory circuits are a viable option. The main technologies used in the fabrication of memory circuits are EEPROM and FLASH, which are compared in Table 2.

4.3 Analog-to-digital converters

Commonly, sensors give an electrical output in form of voltage or current that is proportional to the measured parameter. However, this analog value can't be directly processed by a microcontroller, which creates the need of a device that can convert this continuous-time value in a digital, binary-coded form. This device is the analog-to-digital converter, popularly known as ADC.

Despite the variety in ADCs, their performances can be summarized by a relatively small number of parameters [66]. Within these parameters, resolution is the most important one, and is defined as the number of bits of the binary-coded parameter. The higher this number is, the more precise the sampled value will be.

Most microcontrollers have ADCs with 10–12 bit resolution, which is enough for most applications. However, if the parameter being measured needs higher precision, an external ADC can also be used.

Another parameter to be checked for is the number of ADC ports available, as each sensor uses one port. In USNs, it is common to measure multiple sensors in a single node, so it is important to take into account the number of ADC ports available in the microcontroller.

4.4 Digital interfaces

Another feature that most microcontrollers present, and that is essential to the functioning of processing units, are digital interfaces, that is, peripherals that enable the communication between devices. Some of the most common digital interfaces include universal asynchronous receiver/transmitter (UART), I^2C, SPI and IrDA.

Universal asynchronous receiver/transmitter, is a hardware that controls serial communications. The transmitter takes bytes of data and sends it in a serial stream of bits. On the other hand, the receiver reassembles the bits in the form of bytes. This peripheral is of great importance because serial communications are primarily used in modems, microcomputers and others. It enables the processing unit to communicate with a variety of devices. It is becoming common for microcontrollers to present USART, that also permits synchronous communications.

I^2C, is a serial bus commonly used to communicate in embedded systems. It uses two bidirectional lines: serial data line (SDA), and serial clock (SCL). More than one master can attempt to control the bus at the same time without corrupting the message [1], making it multi-master. Microcontrollers must have hardware that enable I^2C communications.

Serial peripheral interface (SPI) is another bus used in embedded systems for serial communications. It operates with a single master and multiple slaves, and slaves are selected through a chip select line. It uses three lines: SCLK, for serial clock; MOSI/SIMO, the output signal from the master; MISO/SOMI, the output signal from the slave. In comparison with I^2C, it achieves higher throughput, despite supporting only one master, and is also more typically used for board-level communications.

Another digital interface that is growing in importance is IrDA, that handles infrared communications. However, it is not commonly used in USN's processing units.

4.5 Real time clocks

In sensor networks, synchronizing operations of all nodes is paramount for efficient communications. Hence, we need to equip the nodes with clocks. The real time clocks (RTCs) are integrated circuits widely used in electronic systems. They can be used to provide time-stamps for sensed data, as well as timing needed by the implementation of protocols.

Recently, atomic clocks have been developed, having a greater precision than normal RTCs. These devices provide the accuracy and stability of atomic clocks, while maintaining small sizes and low power consumption [58]. The use of atomic clocks helps to facilitate the problem of network synchronization that is very important in many applications and UWSN protocols.

The nodes can be synchronized before deployment. This way, the precision of atomic clocks guarantees synchronization of all network nodes for a long period of time, which is very useful in localization [37–39] and communication [44] protocols.

5 Sensing unit

The main function of the USN is to perform measurements of water parameters. This is accomplished with the sensing unit, a group of sensors chosen based on the application requirements.

Here we describe sensors that are generally used in sensing units, focusing on water quality sensors. We first give a broader view on the seven most used types of sensors: pH, conductivity, dissolved oxygen, temperature, turbidity, chlorophyll and salinity sensors. Then we list other types of sensors, citing the main applications in which they are used.

Table 3 pH sensors comparison

Manufacturer/model	Current (mA)	Output (mA)	Size (cm)	Weight (g)	Range
Global Waters WQ201 [3]	16.6 plus output	4–20	3.18 diam. × 25.4 length	435	0–14
ECD PH10 [34]	–	–	1.9 diam. × 34.9 length	1130	0–14
Analion P620N [22]	–	–	1.2 diam. × 12 length	500	0–14

Table 4 Conductivity sensors comparison

Manufacturer/model	Current	Output	Size (cm)	Weight (g)	Range (mS/cm)
Global Waters WQ301 [3]	0.8 mA plus output	4–20 mA	2.54 diam. × 30.5 length	227	0–20
Mostec M8836S-10 [47]	–	–	4.7 diam. × 14.4 length	–	0.05–200
Omega CDE-45P [11]	–	–	3.68 diam. × 22.53 length	450	0–2000
Vernier CON-BTA [12]	–	–	1.2 diam. × 15 length	–	0–20

5.1 pH sensors

pH is the measure of hydrogen ions in a solution. When measured in a lake or river, for example, it indicates the acid and base characteristics of the stream. The neutral value for water's pH is 7.0. Lower values mean acidic solutions, while greater values indicate alkaline solutions.

pH measurements are important in applications that range from medicine to engineering and environmental. So, pH sensors are one of the most frequent type of sensors present in a sensing unit. It is specially important to measure pH in aquatic environments because it is a indicative of algal blooms, nutrient deficiencies and metal toxicities in water, all of them which can damage aquatic life. Table 3 shows a comparison of commercial pH sensors.

Here and in all tables listing commercial sensors that follow, we described the most relevant parameters when designing a sensor node: current consumption in mA; the output signal or communication protocol in the case of digital sensors; the physical size that the sensor occupies; the sensor's weight; the range in which the sensors can operate.

5.2 Conductivity sensors

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

As water temperature varies, so does the electrical conductivity, which varies circa 2–3 % per Celsius degree in a direct relationship. Thus, in choosing electrical conductivity sensors one must verify if it includes temperature compensation methods in its design. Table 4 compares the conductivity sensors.

5.3 Dissolved oxygen sensors

Dissolved oxygen or oxygen saturation measures how much oxygen is dissolved in water. Aquatic fauna needs adequate dissolved oxygen levels to survive. It is also pivotal to the sus-

Table 5 Dissolved oxygen sensors comparison

Manufacturer/model	Current (mA)	Output (mA)	Size (cm)	Weight (g)	Resolution (ppm)
Global Waters WQ101 [3]	11.8 plus output	4–20	3.18 diam. × 27.94 length	450	–
Sensorex DO7400 [55]	–	4–20	5.72 diam. × 17.8 length	–	0.5–20
Digitrol dTRANS002 [32]	–	4–20	4 diam. × 19.3 length	–	0–50

Table 6 Temperature sensors comparison

Manufacturer/model	Current (mA)	Output (mA)	Size (cm)	Weight (g)	Range (°C)
Global Waters WQ101 [3]	20 mA	4–20 mA	1.9 diam. × 11.4 length	227	−50–50
Campbell Scientific Companies 109SS-L [25]	–	–	1.02 diam. × 4.24 length	150	−40–70

tainability of entire water ecosystems. Low levels of dissolved oxygen, called deoxygenation, are responsible for growth of anaerobic bacteria and algae that results in massive fish killing. Because of this, it is one of the most common indicators of water quality, and measuring this parameter is fundamental in monitoring aquatic environments.

The main factors responsible for changing dissolved oxygen levels are related to waste water and aquaculture facilities. Table 5 shows a comparison of dissolved oxygen sensors.

5.4 Temperature sensors

Adequate temperature is vital for all forms of life, and this holds for aquatic life. It determines what kinds of organisms will proliferate in the environment. Therefore, monitoring temperature allows for modeling population dynamics of rivers, lakes and oceans.

Other important application of temperature monitoring is associated with water chemical characteristics [57]. The rate in which dissolution occurs in water is directly proportional to temperature. Minerals will dissolve more easily in higher temperatures, increasing turbidity and electrical conductivity, for example. The inverse effect occurs with gases, which causes dissolved oxygen to diminish in high temperature waters, leading to aquatic life killing. Table 6 compares the temperature sensors.

5.5 Turbidity sensors

Turbidity indicates the amount of suspended particulate matter that causes light to scatter in water. Common suspended sediments are clay, plankton, microscopic organisms, soil and silt. These elements can be naturally present in water or can be contaminants from other site, like agriculture plants. The sediments can also contain pollutants like pesticides.

Turbidity is commonly measured through shining a light through water. The amount of light perceived in another sensing, commonly indicated in nephelometric turbidity units (NTU), gives an indication of the water's turbidity. 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. Table 7 compares the turbidity sensors.

Table 7 Turbidity sensors comparison

Manufacturer/model	Current (mA)	Output (mA)	Size (cm)	Weight (g)	Range (NTU)
Global Waters WQ370 [3]	30 mA plus output	4–20mA	3.8 diam. × 21.6 length	454	0–1000
Green Span TS3000 [56]	35 mA	SDI12	4.7 diam. × 41.8 length	500	0–1000
Analite 9000 [23]	15 mA	−2.5–2.5 V	3.2 diam. × 18.2 length	380	0–3000

Table 8 Chlorophyll sensors comparison

Manufacturer/model	Current (mA)	Output (V)	Size (cm)	Weight (g)	Range (μg/L)
Hydrolab Chlorophyll sensor [2]	–	0–5	–	–	0–500
Wetlabs WETStar [7]	40–80	0–5	6.9 diam. × 17.1 length	800	0.03–75
Seapoint SCF [17]	15–27	0–5	6.4 diam. × 16.8 length	850	0.02–150
YSI 6025 [71]	–	–	–	–	0–400

Table 9 Salinity sensors comparison

Manufacturer/model	Output	Size (cm)	Weight (g)	Range (ppm)
Vernier SAL-BTA [15]	–	1.2 diam. × 12 length	–	0–50,000
Partech C4E [9]	RS485	2.7 diam. × 17.7 length	350	0–60,000
CMA ML66M [16]	I2C	1.8 diam. × 6.2 length	350	0–50,000

5.6 Chlorophyll sensors

Chlorophyll is a substance encountered in cyanobacteria, like blue–green algae, and plants. It is a critical element to perform photosynthesis, which is the mechanism by which plants produce its own energy from light. This parameter indicates the concentration of phytoplankton in water, and leads to the understanding of water's trophic state index. This index is determined by the quantities of biological nutrients present in water.

The chlorophyll measurement is also useful for identifying and predicting algae blooms. Table 8 compares the chlorophyll sensors.

5.7 Salinity sensors

The concentration of dissolved salts in water is called salinity. While both fresh water and ocean water have dissolved salts in it, the second one presents a much higher dissolved salt concentration, and thus higher salinity.

Salinity influences the kinds of organisms that live in water, so it is a fundamental parameter in monitoring water streams. Table 9 compares the salinity sensors.

Table 10 List of water sensors

Parameter	Description
Ammonium chloride	Form of nitrogen. It can accelerate growth of algae and aquatic plants
Acoustic Doppler current profiler	Measures water current, using the Doppler effect associated with ultrasonic waves to do so
Blue green algae	Cyanobacteria that can be blue, green, red or black. Produces toxins and can reduce dissolved oxygen in water
Chloride	As a component of salt, chloride is commonly encountered in water, but high levels of this ion can damage aquatic life
Crude oil	Commonly known as petroleum, crude oil is a liquid composed of hydrocarbons that can damage aquatic life when in excess
Free chlorine	Also known as hypochlorous acid, free chlorine must be monitored in potable water
Hydrocarbon	Levels of hydrocarbons must be monitored near oil exploration sites, seaports and whenever they have contact with water streams
Nitrate	Nitrate is a common ion on water, but high levels can cause death of fish and intoxicate humans
Oxidation reduction potential	Determines the reducing potential of water, and is used to indicate industrial waste contamination
Photosynthetically active radiation	Amount of light that diffuses through water. It is used to monitor aquatic flora dynamics
PTSA Dye	The P-Toluene Sulfonic Acid is commonly present in detergent products and can contaminate water
Refined Fuels	Fuels derived from crude oil that can be toxic to the aquatic ecosystem
Rhodamine water tracing	A form of red dye used to determine how the water flows
Total dissolved gas	Monitoring the total pressure of gases is important to avoid supersaturation that can cause massive fish kills

5.8 Other sensors

pH, conductivity, dissolved oxygen, temperature, chlorophyll and salinity are the most common water quality parameters, and should be first considered to compose a sensing unit of a USN designed to monitor masses of water. Nevertheless, there are other parameters of great importance for a good understanding of the water quality. Table 10 indicates these parameters, giving a brief description of them.

6 Power supply and energy management unit

We now describe power supply and energy management unit. This unit's main modules are: power source, charge estimators and management modules. They are depicted in Fig. 4. Next, we describe each module in more detail.

6.1 Power sources

The power source is primarily responsible for providing energy to the sensor node. Because of weight and size constraints, special care should be taken choosing the main power source.

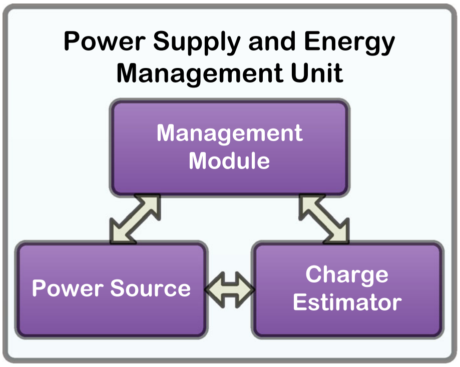

Fig. 4 Power supply and energy management unit modules block diagram

Table 11 Batteries comparison

Battery	Voltage per cell (V)	Energy density (Wh/L)	Rechargeable
Alkaline	1.5	450 [18]	No
Carbon zinc	1.5	156 [18]	No
Zinc air	1.35	890 [18]	No
Nickel metal hydride	1.2	343 [18]	Yes
Lithium ion	3.6	396 [18]	Yes
Lithium polymer	4.2	220 [36]	Yes
Nickel cadmium	1.5	100 [36]	Yes
Lithium iron phosphate	3.9	150 [36]	Yes

Generally, these constraints lead to the choice of batteries. Hence, here we take a brief look on the most common battery technologies used nowadays.

Table 11 compares some battery types. We see that zinc air batteries present higher energy densities, and thus are a good choice. However, it is not rechargeable. Among rechargeable batteries, lithium ion has the highest energy density.

6.2 Management modules

Other than the power source, the sensor node must control how much energy it uses, in order to remain active for as long as possible. This is generally accomplished with a management module.

The management module shuts down devices when they are not being used. For this, the microcontroller must have low power states. Also, sensors and modems must be physically wired to a switch, like a transistor, in order to be properly shut down.

6.3 Charge estimators

Charge estimators inform how much energy remains in the sensor node. They measure voltage, current and temperature of the battery in order to determine the battery state of charge (SOC). There are two basic methods for doing SOC estimation [49]: the discharge method and the coulomb counting (ampere hour counting) method.

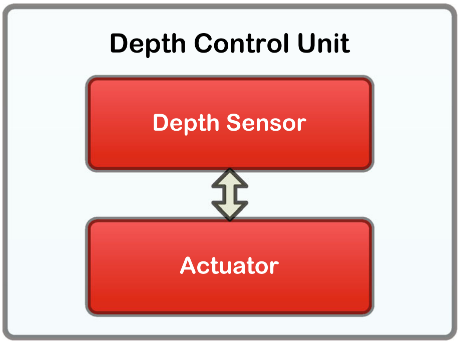

Fig. 5 Depth control unit modules block diagram

The discharge method is based on the discharge curve of the battery, that relates voltage with remaining charge. Hence, one should read the battery voltage and compare it with the battery discharge model, giving an indication of the SOC.

The coulomb counting method is the most common SOC estimation method. It performs a summation of current over time, which indicates how much charge the battery lost.

Other methods includes stochastic approaches, employing Kalman filters to perform SOC estimation [52].

7 Depth control unit

Depth control units, schematized in Fig. 5, are composed of two main modules: the depth sensor, which measures pressure underwater and calculates the depth, and the actuator, which guides the node along a column.

There are two ways to implement the depth control unit. One is to have a pressure sensor and the MCU reads the values and computes the depth. The other is to have a stand-alone system, with a dedicated MCU.

Effective understanding of aquatic environments requires extensive knowledge of water parameters along the water column. To be able to sense these parameters, the sensor node must have a depth control unit.

Not all sensor nodes have a mechanism that enable them to move in water. However, although not strictly necessary for the node's operation, depth control units can greatly extend its capabilities. Because of the different characteristics of the water, changing depth can also help improving the communication channel, as pointed out in [31]. Also, it can help in routing protocols, as shown by Coutinho et al. [28].

Next we extend some points associated with depth control units, and also make a brief review on available solutions.

7.1 Depth sensor

To control the node's depth, it is necessary to have depth information feedback, which is generally accomplished using a depth sensor. Also, the sensor must be coupled to the node's body, so it must have a measurement principle that functions well with the sensor in water.

To fulfill these requirements, pressure sensors are generally used to measure water depth. It functions as follows. In one hand, the sensor measures water pressure while, on the other hand it measures a vacuum. This gives an absolute pressure value, which is subtracted form atmospheric pressure in order to indicate water's gauge pressure. Then, this pressure is used to calculate depth.

It must be noted that as temperature and density varies, the pressure and hence the depth measurements will also vary. So, we must compensate these factors via calibration or other similar procedures in order to have a correct depth measurement.

7.2 Actuator

Besides the sensor, the depth control units must have an actuator that moves the node up and down.

There are a few possibilities that enable the node to move under the water. First, one can include a propeller in the node's design. The propeller moves the node freely, three-dimensionally. While very flexible, this alternative is also very costly in terms of energy. The design of the node is also more complex.

Bladder driven depth actuators function as follows. A pneumatic or hydraulic circuit is built in the node. This circuit actuates an air bladder that, depending on the air volume, varies the node's depth. Examples of bladder driven depth actuators include ARGO [61] and the AUE [42].

Another type of depth actuators use an anchor line, like [31]. Here, the sensor node is fixed in an anchor line, and a motor guides the node along this line.

8 Housing

Here we give a general view on the node's housing, citing requisites that it must satisfy to guarantee the good functioning of the node. Then, we list some of the commercial available solutions.

8.1 Requirements

The housing is not discussed very much in the design of terrestrial sensor nodes, but is of paramount importance to design good USNs. This is due to the fact that water presents greater danger to the electronic devices used in the construction of the node.

The main requirement for the USN housing is to be waterproof, providing tightness. Hence, pressure is the main factor to be considered, because as pressure goes up, more complex the housing will be, in order to guarantee tightness.

Also, mechanical shock constraints should be considered if the node will be deployed in an area where it may shock with solid objects, or the bottom of a lake, for example. In this situation, one must design the housing with the capability to resist such impact.

8.2 Available solutions

There are mainly two types of housing: box shaped and cylindrical shaped ones. These are shown in Fig. 6. Cylindrical shaped housings are used more often, as used in the nodes built in [62,67,68]. Box shaped housing is used in [45].

The most common materials used in the housing construction are plastic, stainless steel and glass, such as [24]. These choices are justified by the fact that the material needs to present high resistance to water corrosion. In choosing one of these alternatives, the following factors must be analyzed: durability, mechanical shock resistance, cost and weight.

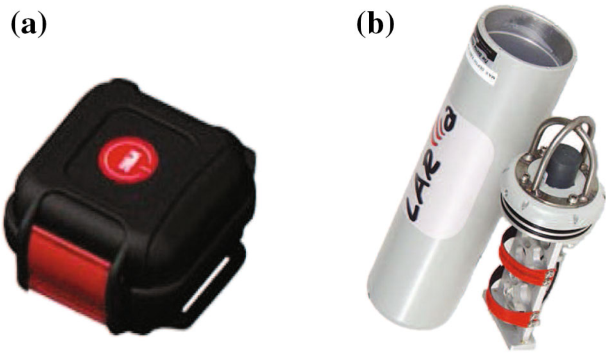

Fig. 6 Types of housing. **a** *Box shaped* housing. Image from [43]. **b** *Cylindrical shaped* housing . Image from [26]

Stainless steel is more durable and presents higher mechanical shock ratings than plastic. However, it is more expensive and weights more. So, if the solution needs to be low cost and durability and shock constraints are not so important, plastic is the way to go. However, if the node must endure long periods of time, stainless steel is the more appropriate choice.

If one does not want to project its own housing, there are companies that sell pre-molded or custom ones. Some of these companies can be found in [26,27,33,43,51,53].

9 Conclusion

In this survey, we evaluated and discussed the various aspects associated with the design of underwater sensor nodes, listing the main challenges and requirements present in the design of USNs.

We proposed a general classifying model for underwater sensor node architectures. This architecture is composed by five interconnected units: processing, sensing, communication, power supply and energy management, and depth control units. Based on this model, we took a brief look on current underwater sensor nodes, analyzing its main function.

We expect that this paper contributes to the area of underwater sensor nodes, serving as a reference for all those who intend to build underwater sensor nodes, developing new UWSN applications and protocols.

Compliance with ethical standards

Conflict of Interest The authors declare that they have no conflict of interest.

Informed consent We consent with the Ethical Standards.

Research involving human participants and/or animals This research does not involve human or animals participants.

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