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An overview of the internet of underwater things

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ABSTRACT

Approximately 71% of the Earth's surface is covered by ocean, a continuous body of water that is customarily divided into several principal oceans and smaller seas. Ocean temperatures determine climate and wind patterns that affect life on land. Freshwater in lakes and rivers covers less than 1%. Its contamination seriously damages ecosystems. The Internet of Underwater Things (IoUT) is defined as a world-wide network of smart interconnected underwater objects that enables to monitor vast unexplored water areas. The purpose of this paper is to analyze how to benefit from the IoUT to learn from, exploit and preserve the natural underwater resources. In this paper, the IoUT is introduced and its main differences with respect to the Internet of Things (IoT) are outlined. Furthermore, the proposed IoUT architecture is described. Important application scenarios that illustrate the interaction of IoUT components have been proposed. Critical challenges have been identified and addressed.

1. Introduction

The Internet of Underwater Things (IoUT) is a technological revolution of computing and communications. It is defined as a world-wide network of smart interconnected underwater objects with a digital entity (Pascual et al., 2011). These devices sense, interpret and react to the environment due to the combination of the Internet, powerful tracking technologies and embedded sensors. It is also possible to interconnect underwater with terrestrial things (e.g. smartphones). Each underwater physical object is accompanied by a rich, globally accessible virtual object that contains both current and historical information on that object's physical properties, origin and sensory context. This information is ubiquitous, available in real-time using different ways of communication (Human to Thing (H2T) and Thing to Thing (T2T)) and streamlines dramatically how to maintain and manage underwater habitats and resources.

In this paper, an in-depth view of the IoUT is provided. Approximately 71% of the Earth's surface is covered by ocean, a continuous body of water that is customarily divided into several principal oceans and smaller seas. Ocean temperatures determine climate and wind patterns that affect life on land. Freshwater in lakes and rivers covers less than 1%. Its contamination seriously damages ecosystems. The IoUT enables to monitor vast unexplored water areas. The purpose of this paper is to analyze how to benefit from the IoUT to learn from, exploit and preserve the natural underwater resources. *Scientific, industrial, military and home security applications* are required. To the best of our knowledge this is the first paper that discusses the IoUT.

The paper is structured as follows. Section 2 introduces the specific characteristics of the IoUT in comparison with its ground-based counterpart (Internet of Things (IoT) (ITU Internet Reports, 2005)). Afterwards, we discuss the proposed IoUT architecture from a technical perspective in Section 3. Next, in Section 4 its application scenarios are described. Later, in Sections 5 and 6 its benefits and main research challenges are outlined, respectively. Finally, in Section 7 the paper is concluded.

2. Characteristics of the Internet of Underwater Things

The Internet of Underwater Things has some similarities with its ground-based counterpart (IoT) (ITU Internet Reports, 2005) such as its structure and function. It is also restricted by the computation and energy limitations of the devices. However, it also has differences, which are summarized as follows.

2.1. Different communication technologies

Radio waves do not propagate well underwater (Cui et al., 2006). The most important restriction of Electromagnetic (EM) communication in freshwater is the large antenna size and in seawater the high attenuation (Liu et al., 2008). Therefore, most communications in the IoUT are based on acoustic links. Although acoustic waves have been widely accepted by the scientific community as underwater physical transmission medium, the large propagation delays of acoustic waves and high bit error rates of the underwater acoustic channel hinder communication.

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In extreme cases, the sound speed variations with depth cause refraction of signals and result in a spatially variant channel. As a result, shadow zones (Domingo, 2008) (see Section 6) are formed, which cause significant bit error rates and loss of connectivity. The available bandwidth of underwater acoustic channels is severely limited and depends on both transmission range and frequency (Cui et al., 2006). Long-range systems that operate over several tens of kilometers may have a bandwidth of only a few kHz, while a short-range system operating over several tens of meters may have more than a hundred kHz of bandwidth (Akyildiz et al., 2005). In addition, acoustic waves are affected by turbulence caused by tidal waves and suspended sediments, acoustic noise and pressure gradients (Che et al., 2010). The negative effects of acoustic propagation especially damage communication in shallow water (water with depth <100 m), since it is adversely affected by temperature gradients, surface ambient noise and multipath propagation due to reflection and refraction (Liu et al., 2008).

2.2. Different tracking technologies

The IoT uses basically Radio Frequency Identification (RFID) for tracking. However, in the IoUT, things (usually fish) are tracked with different technologies depending on the fish size and species, type of data to be collected and habitat utilization, as shown in Table 1 (Dotson, 2009; Smith et al., 2009):

- *Acoustic tags* are sound-emitting devices. They have large detection ranges (up to 1 km in freshwater) and are used to track fish in three dimensions (3-D).
- *Radio tags* transmit a radio-frequency signal detectable through a system of one or more antennas and receivers. They have limited ranges (around 10 m in freshwater) and cannot work in seawater.
- *Passive Integrated Transponder (PIT) tags* are glass-encapsulated, implantable RFID devices. They require an external energy source (reader) to activate the tag for data retrieval. They have a limited detection range (approximately 20 cm in freshwater) and perform poorly in seawater. However, they do not depend on batteries and can be implanted in small fish due to their limited size.

Table 1
Comparison between tracking techniques.

Characteristics	Types of tags		
	Acoustic tags	**Radio tags**	**PIT tags**
Freshwater	Yes	Yes	Yes
Seawater	Yes	No	No
Detection range	Freshwater: 1 km Seawater: 200 m	Freshwater: 10 m	Freshwater: 20 cm
Size			
Length	19–74 mm	20–80 mm	11–28 mm
Diameter	6–16 mm	9–30 mm	2–3.5 mm
Cost	Around $250	Around $250	Around $3
Battery	Yes	Yes	No
Battery life duration	19 day–4 years (depending on the tag ping rate and the battery size)	9 day–3 years (depending on the time between bursts and the battery size)	–
3-D position estimation	Yes	No	No
Store information	No	No	Yes
Need recapture	No	No	Yes

2.3. Difficulty of battery recharge

Underwater objects are prone to failure due to fouling and corrosion. Their battery capacities are limited; compared to most terrestrial IoT objects it is more difficult (sometimes impossible) to recharge or replace them. Ambient energy harvesting combined with supercapacitors is a promising technology to eliminate the need of using batteries and rely only on harvested energy to operate (Seah et al., 2009).

2.4. Different energy harvesting technologies

Two of the most promising energy harvesting technologies for IoT devices are solar energy and piezoelectric harvesting (Gorlatova et al., 2010). Although most IoUT devices cannot exploit solar energy, solar-powered Autonomous Underwater Vehicles (AUVs) are pre-programmed to submerge but also to operate on the surface for battery charging via solar energy input. Piezoelectric energy harvesting can also be exploited in the IoUT. In Taylor et al. (2001), the authors introduce a device that uses long strips of piezoelectric polymers, which undulate in a water flow to convert the mechanical flow energy available in oceans and rivers, to electrical power. In addition, Microbial Fuel Cell (MFC) is an alternative technique for underwater energy harvesting. It exploits metabolic activities of bacteria (such a microorganisms from water) to generate electrical energy directly from biodegradable substrates. In Dai et al. (2011), a new underwater MFC system is designed and implemented. Experimental results demonstrate its potential to power microelectronic devices such as IoUT 'objects' for underwater applications. The IoUT also benefits from specific underwater energy harvesting techniques such as ocean thermal energy. An AUV has been developed by NASA/Scripps Institution of Oceanography, which uses a novel thermal recharging engine powered by the temperature differences found at different ocean depths.

2.5. Different network density

In the IoT it is expected that a very large number of devices communicate if all the 'things' join the network. On the contrary, the IoUT is deemed to be more sparse due to the cost and challenges associated to an underwater deployment (Akyildiz et al., 2005). As a result, communication establishment and maintenance between different IoUT devices becomes more difficult.

2.6. Different localization techniques

The location of mobile devices in the IoT is afforded by Global Positioning System (GPS) satellites. However, GPS uses radio waves in the 1.5 GHz band that do not propagate in water. Consequently, different localization techniques for the IoUT are required. Localization approaches proposed for ground-based sensor networks do not work well underwater because long propagation delays, Doppler effect, multipath and fading cause variations in the acoustic channel (Akyildiz et al., 2005). Bandwidth limitations, node mobility and sparse deployment of the underwater nodes also affect localization estimation. Proposed terrestrial localization schemes based on Received Signal Strength (RSS) are not recommended in underwater wireless sensor networks, since non-uniform acoustic signal propagation causes significant variations in the RSS. Other terrestrial localization approaches based on Time of Arrival (ToA) and Time Difference of Arrival (TDoA) measurements require very accurate time synchronization (which is a challenging issue) and the localization mechanisms based on Angle of Arrival (AoA) algorithms are affected by the Doppler shift. However, valuable insight has been gained into this area and several localization techniques specifically designed for underwater wireless sensor networks that do not rely on time synchronization have been proposed (Cheng et al., 2008, 2009; Liu et al., 2010; Luo et al., 2010).

The Localization with Directional Beacons (LDB) scheme (Luo et al., 2010) uses an AUV as a mobile beacon sender. The sensor nodes can localize themselves silently by listening to two or more beacons sent from the AUV. UPS (Cheng et al., 2008), a silent underwater positioning scheme, relies on the time arrivals of beacon signals locally measured at a sensor to detect range differences from the sensor to four anchor nodes. These measurements are averaged to estimate the 3-D sensor location through trilateration. In Cheng et al. (2009), a localization scheme designed for large scale underwater wireless sensor networks is introduced. Large-Scale Localization Scheme (LSLS) relies on TDoA measurements calculated locally at a sensor to measure the range differences from the sensor to three anchors that can hear each other. In Liu et al. (2010), the Asymmetrical Round Trip based Localization (ARTL) algorithm is proposed for localization in large-scale underwater wireless sensor networks. It uses ToA measurements to obtain the distance between ordinary nodes and beacon nodes (powerful nodes that can directly contact the surface base station and are capable of self-localization).

3. IoUT architecture

The proposed IoUT architecture is shown in Fig. 1. It is divided into three layers, whose basic functionalities are summarized as follows:

- *Perception layer*: It identifies objects and gathers information. It is formed mainly by underwater sensors, underwater vehicles, surface stations (sinks), monitoring stations (such as tablet PC, smartphone, etc.), data storage tags, acoustic/radio/PIT tags and hydrophones/receivers/tag readers.
- *Network layer*: It consists of a converged network made up of wired/wireless privately owned networks, Internet, network administration systems, cloud computing platforms, etc. It processes and transmits the information obtained from the perception layer.
- *Application layer*: It is a set of intelligent solutions that apply the IoUT technology to satisfy the needs of users.

Next, we describe in greater detail the components of each layer.

3.1. Perception layer

We distinguish between different components.

3.1.1. AUVs and underwater micro and nanosensors

AUVs are unmanned underwater vehicles, which operate independently of direct human input. We can distinguish between autonomous vehicles able to operate (1) on the surface layer (Autonomous Surface Vehicles (ASVs)), (2) AUVs operating in the interior and (3) AUVs operating on the bottom layer. The most important subsystems of an AUV are platform, navigation, control, energy, communication and sensors (Curtin et al., 2005). AUVs operating on and in navigable waters should be able to estimate their position and avoid collisions. Controlling an AUV with autonomy and intelligence is especially challenging in the presence of other nearby moving vehicles. Therefore, mastering the International Regulations for Preventing Collisions at Sea (COLREGS) is essential to navigate safely (Curtin et al., 2005). They are fitted with sonar sensors for assisted navigation. *Underwater sensors* and *AUVs*

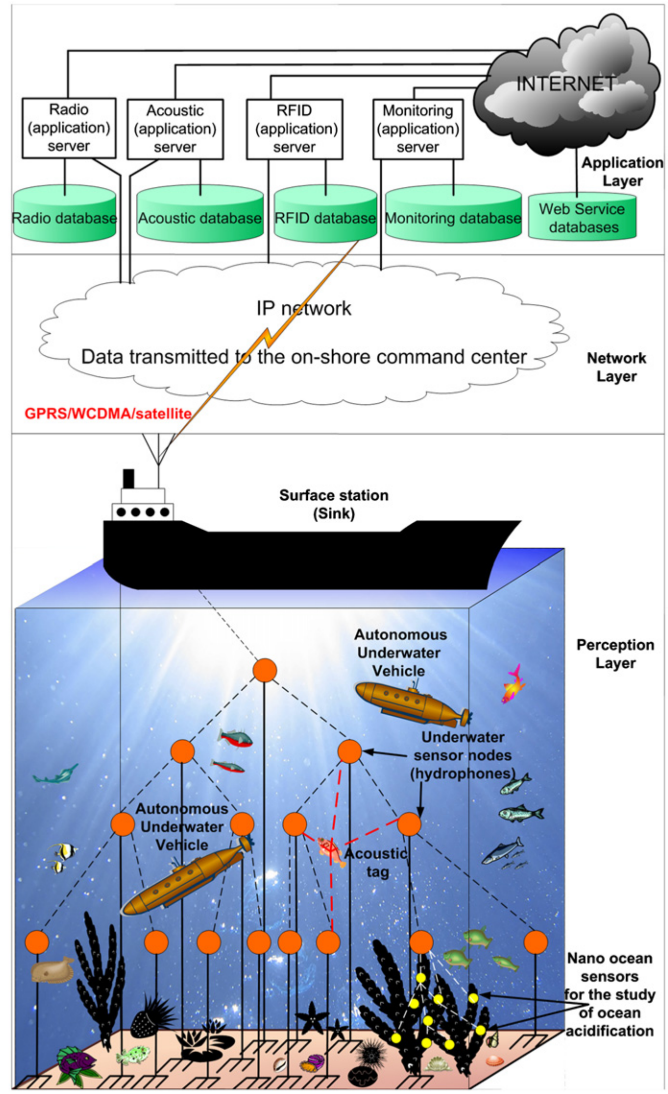

Fig. 1. Proposed architecture.

(see Fig. 1) interact together in specific applications such as oceanographic data collection, collaborative monitoring or surveillance. They measure ocean processes and signals of interest. This cooperation is very useful in sophisticated tasks such as large-scale long-term perception of the environment and reaction to environmental changes. The sensed data is sent to the surface station (sink), which floats on the water surface and uses long distance radio communication to send this data to an onshore station. The onshore station is located at the monitoring center and performs further analysis of the data. It is expected that based on research the size of *sensors* is reduced to the *microscale* and finally to the *nanoscale* size (a few nanometers). *Nanosensors* make use of the unique properties of nanomaterials and nanoparticles to detect and measure new types of events in the *nanoscale* (Akyildiz and Jornet, 2010). *Nanotechnology* is very promising for ocean monitoring (Mongillo, 2007). Human activities such as combustion of fossil fuels have led to a new flux of CO_2 into the atmosphere, which is partially being absorbed by the oceans. Consequently, the seawater acidity is increased (pH is lowered). Ocean acidification has changed ocean chemistry in ways that especially threaten certain marine organisms, since it is harder for them to form their skeletons or shells. *Nano-enabled marine sensors* sense the dissolved CO_2 to monitor this phenomenon.

3.1.2. Acoustic tags

An *acoustic tag* is a small sound-emitting device. It can be gastrically inserted in or surgically implanted into the fish (or almost any aquatic life). It transmits periodically a ping at a specific rate to an array of hydrophones (acoustic sensors or AUVs), which is forwarded to the sink using the sensor network. Each fish is encoded with a unique digital ID using a signaling scheme (e.g. Differential Phase-shift Keying (DPSK)). A ping is detected by each hydrophone at slightly different arrival times depending on how far the fish is from each hydrophone. These time differentials are used to triangulate the 3-D position of fish such as salmon. Salmon live most of their lives in the ocean, but migrate to reproduce in rivers. When they reach the spawning grounds swimming upriver, they mate, lay eggs, and die shortly thereafter. After the eggs hatch, the born young fish, called smolts at this stage, swim downriver to the ocean and spend years traveling around. In Steig and Johnston (2010), *acoustic tags* are used to track the downstream migration of salmon smolts in the Columbia River. They are tracked in 3-D as they approach and pass into the turbine intakes, spillways and surface bypass channel entrances at the dams of the river. This way, their survival rates are estimated. Innovative methods developed in the past years (such as fish density algorithms and advances in three-dimensional animation and visualization programs) are used to analyze fish behavior and movement.

In Ehrenberg and Steig (2001), a method is developed to predict the accuracy of the position measurements provided by an acoustic tag system. The primary factors that affect accuracy are the position of the tag relative to the location of the hydrophones, the noise level relative to the tag-signal level at the hydrophones and the inaccuracies in the assumed sound velocities in water. In Ehrenberg and Steig (2001), the 'position accuracy' of acoustic tags is computed without any need for field measurements or Monte Carlo simulations. This method can be helpful during the design phase to select the number of hydrophones required and their optimal positions to minimize position errors prior to the deployment of the acoustic tag measurement system. In Ehrenberg and Steig (2009), a complete study is performed where the optimal acoustic tag operating and design parameters are identified. The ranges at which the tags can be detected and uniquely identified, the positional accuracy and the number of unique codes that can be assigned to individual fish have been studied as functions of the tag-signal type.

3.1.3. Radio tags

Radio tags transmit a radio-frequency signal, which can be detected above the water (boat).

Seawater is a high lossy medium where the electric conductivity is about two orders higher than that of freshwater mainly due to its high salinity. *Radio tags* (as opposed to acoustic tags) become less effective in high conductive water. In freshwater, despite the limited range (around 10 m), EM waves (as opposed to acoustic waves) are tolerant to turbulence caused by tidal waves and suspended sediments, immune to acoustic noise and unaffected by pressure gradients. Therefore, *combined acoustic-radio tags* are the best option to track subjects moving between both salt and freshwater. This is the case of fish that migrate to and from different environments (for example, through riverine, estuarine and marine environments, or from fast flowing rivers in the spring to deep lakes and reservoirs during the summer). This is especially true for the smolts, juveniles and sub-adults of such species. The combined acoustic-radio tags eliminate the need to double-tag the study subjects. Through advanced programming the optimal transmission mode (radio or acoustic) can be adjusted.

3.1.4. PIT tags

A *PIT-tag* system consists of the tag, antenna, and transceiver. Each *PIT tag* contains an individual alphanumeric code to identify the fish. The small size of PIT tags does only have little or no influence on fish growth, behavior, health, or predator susceptibility. The short detection ranges require that fish are steered to a particular sensing area for tag reading using RFID. The passive circuitry of the PIT tag is energized when the tag enters within the radiating electronic field of the reader. Excited by the low-frequency radio signal (134.2 kHz), the transponder inside the PIT tag relays the code signal from the tag's microchip back to the reader. The reader decodes the unique ID number from the PIT tag and sends it to a computer for further processing.

Since *PIT tags* are passive, they remain functional for the life of the fish. Thus, in the case of salmon, the tag still works in the salmonid when it returns from the ocean, migrating upstream to its spawning grounds. As the adult passes through the fish ladders at each dam, the *PIT tag* is read and the data is correlated with information collected when the fish was a juvenile, years before. Through this unique technology smolt-to-adult return rates are calculated. Some research projects mark only a few dozen fish during the field season, whereas up to 20,000 fish are tagged in a day in other larger research projects.

3.1.5. Data storage tags

Data storage or archival tags can be attached both internally and externally on the fish. They gather time, temperature, salinity and depth data. The data is stored in an internal memory. At the end of the monitoring period the loggers can be connected to a computer and the data is extracted for analysis.

3.2. Network layer

This layer enables the access of the surface station (sink) over the sea to the radio channel to process and transmit the required information obtained from the perception layer. This information is retransmitted to the onshore command center using a variety of access networking technologies such as satellite communications, General Packet Radio Service (GPRS) or Wideband Code Division Multiple Access (WCDMA). Other wireless technologies are intended for short range communications in other scenarios (e.g. for the monitoring stations (such as cell phone, tablet PC, smartphone, PDA, etc.) in the aquarium scenario described in Section 4.1). The different short range communication standards include Bluetooth (IEEE 802.15.1), Ultra-wideband (UWB) (IEEE 802.15.4a and ECMA-368) and ZigBee (IEEE 802.15.4). Finally, Wireless Local Area Networks (WLANs) (IEEE 802.11 variants) and Worldwide Interoperability for Microwave Access (WiMAX) (IEEE 802.16) are used to provide wireless Internet access throughout a local and a metropolitan area, respectively. All these wireless networks that use different access technologies are named *heterogeneous networks*. They are essential in the development of the IoUT and need to maintain connectivity and service in case of mobility.

Although interconnecting underwater 'objects' to the current Internet has a great potential for the development of useful and attractive underwater applications, it is also very challenging. Underwater wireless communication networks lack from some common basic assumptions from the current Internet such as (Potter et al., 2011): (1) availability of end-to-end path between source and destination for the duration of a communication session, (2) timeout and latencies are small (or at least limited), (3) full-duplex communications, (4) channel coherence times longer than packet lengths, (5) small end-to-end error rates (or at least limited) and (6) a communications performance enough to support applications.

In addition, IP is recommended as a long-lived, stable, versatile and ubiquitous protocol to support the wide range of applications and communications technologies of *heterogeneous networks* (Dunkels and Vasseur, 2010). However, not all underwater sensor nodes support IP. Therefore, new protocols that provide interoperability between heterogeneous sensors as well as efficient gateways that enable communication between different transmission media (underwater acoustic and radio/satellite) are required (Potter et al., 2011).

Delay-tolerant networking (DTN) addresses technical issues in heterogeneous networks without continuous network connectivity. Underwater wireless communication networks can be viewed as Delay Tolerant Networks (DTNs) due to their sparse deployment, node mobility and a severely impaired bandwidth-limited underwater acoustic communications channel.

A DTN architecture has been developed (Fall and Farrell, 2008) to accommodate network connection disruption and to provide a framework for dealing with heterogeneous sensor network gateways. In this architecture (Fall and Farrell, 2008), different IP and non-IP based protocols (TCP/IP, raw MAC protocol, serial line, etc.) can be used for data delivery. A collection of protocol-specific Convergence Layer Adapters (CLAs) provides the functions necessary to carry DTN protocol data units (named bundles) on each of the corresponding protocols (Fall and Farrell, 2008). The routers that handle bundles in a store and forward manner are named bundle forwarders or DTN gateways. The bundle architecture therefore operates as an overlay network that provides message delivery service to interconnect heterogeneous portions of a larger network.

DTN2 is the name for a reference implementation of the DTN protocols. In Merani et al. (2011), an Underwater Convergence Layer (UCL) for the DTN2 research platform has been designed and implemented. DTN2 primarily implements the DTN Bundle Protocol (Scott and Burleigh, 2007) to transmit data over several layers in the form of bundles (a series of contiguous data blocks). The proposed UCL (Merani et al., 2011) has been developed to interconnect traditional IP-based and acoustic networks. The software developed is suited for heterogeneous scenarios with gateways that link underwater acoustic nodes and surface nodes that communicate via radio. It can also be used for data mules between AUVs and other underwater devices, where data mule in DTN refers to the exchange of data among 'objects' that do not implement the TCP/IP protocol stack. It can also be extended to support multiple MAC protocols or different acoustic modems. UCL was successfully tested during a sea trial (Merani et al., 2011).

Routing protocols should be designed to support the requirements of a given application. The availability of network resources affects their performance. Routing is specially challenging in underwater wireless communication networks due to the large propagation delays, the low bandwidth, the difficulty of battery refills of underwater sensors, and the dynamic topologies. Therefore, routing protocols in the IoUT should be designed to be energy-aware, robust, scalable and adaptive. The number of control messages and packet overhead should also be minimized. Self-organization and self-maintenance are essential properties to ensure robustness. Mechanisms to establish and maintain communication between different underwater devices (e.g. sensors and AUVs) as well as with surface stations (that serve as gateways for above-water networks) are required. A complete survey and comparison of different underwater routing techniques can be found in Ayaz et al. (2011).

3.3. Application layer

The Web of Things (WoT) is a vision where smart objects are integrated with the Web. Smart object applications can be built on top of Representational State Transfer (REST) architectures (Fielding and Taylor, 2002). The REST architectural style decouples applications from the services they provide, which can be shared and reused. The key abstractions of information in the REST architecture are resources (e.g. a document or image). Resources in web-based REST systems are identified by Universal Resource Identifiers (URIs). REST-style architectures consist of clients and servers. Clients initiate requests to servers; servers process these requests and return the appropriate responses. Resources are accessed by clients using methods such as GET, PUT, POST, and DELETE of Hypertext Transfer Protocol (HTTP). The resources themselves are conceptually separate from the representations that are returned to the client. For example, the server does not send its database, but rather, perhaps, some HyperText Markup Language (HTML), Extensible Markup Language (XML) or JavaScript Object Notation (JSON) that represents some database records depending on the details of the request and the server implementation.

A REST-style architecture can be used to represent and access data from IoUT devices (vehicles, sensors, etc.). This way, all nodes are able to request and provide services. Human operators can control these objects using the web. In Pinto et al. (2010), this open web-based architecture has been designed and implemented. It is composed of heterogeneous unmanned vehicles (AUVs, Autonomous Surface Vehicles (ASVs), Remotely Operated Vehicles (ROVs), Unmanned Air Vehicles (UAVs)), environment (surface) sensors, actuators and human operators that connect continuously or sporadically to the Internet. It provides service discovery, service integration and cooperation using ubiquitous web technologies. Due to the heterogeneity of components a modular software system has been developed (Pinto et al., 2010). Inter-Module Communication (IMC) is a message-oriented protocol designed to interconnect vehicles, sensors and human operators. It consists of a unified specification of message structures (a single XML file). The same onboard software (DUNE) is adapted to each vehicle, since it includes specific hardware drivers and vehicle-specific motion controllers. DUNE is composed of various asynchronous tasks that communicate with one another through IMC messages. The state of each node depends on a set of resources. For instance, the state of an unmanned vehicle is related to the state of its onboard sensors, the mission plan, the map of the environment, the commands sent by the human operator, etc. The state of each node evolves from the current state using the feedback from the environment (interaction with other nodes/new operator commands, etc.).

A REST-style architecture to access and represent data from IoUT objects is proposed. Each resource can be represented as a list of name-value pairs. For instance, a vehicle's position is a resource that includes latitude, longitude and altitude fields. Resources can be classified as (Pinto et al., 2010): (1) periodic data obtained from sensors, (2) static data (such as environmental maps or network configurations) and (3) queries (to aggregate data, list state of resources, etc.). When a node is queried about its resources, a list of resource identifiers together with their use is obtained. The resources are serialized into IMC message structures and transmitted using a self-describing format through HTTP (Pinto et al., 2010). Resources are identified following the REST-style approach by one or more URLs that contain the resource, a path that contains the resource identifier, a desired serialization scheme (optional) and specific query parameters. For instance, http://192.168.1.37/dune/imclPosition.xml corresponds to the last Position message that was generated in the vehicle at address 192.168.1.37 in XML format. More examples can be found in Pinto et al. (2010). Resources can be consulted or overridden using HTTP GET and PUT methods, respectively. A HTTP Forbidden (3xx) error response or a HTTP Success (2xx) is received depending if the user is authorized to change the resource or not. For applications that require real-time state updates (like sensor data sharing) HTTP streaming is used for data transmission. Central repositories are created. They use the Atom standard, a simple HTTP-based protocol for creating and updating web resources. Atom is used to list identifiers of existing resources in the network, their URLs and timestamp of the latest changes (Pinto et al., 2010).

In the application layer (see Fig. 1) the services are run by servers, which host and execute them. We have identified some important application servers in the IoUT. The *acoustic server* acquires tag data from different hydrophones. Post-processing software delivers the 3D fish track, survival rates, travel times, etc. The acoustic database stores and updates the fish species, swimming patterns and path achievement during migration.

Similarly, the *radio* and *RFID servers* process radio/PIT tag data to identify the fish and evaluate related information. The radio and RFID databases store and update this data.

The *monitoring server* offers application codes (such as Ajax) to process the sensed data the professionals wish to control. Periodic reports and visual graphs are sent to onshore stations of the monitoring center or monitoring stations of users. The sensor nodes serve the data through web services according to the preferences of the user. For instance, a biologist may be interested in tracking the 3-D position and analyzing data concerning migrating fish; an operator may want to obtain statistics related to water quality.

4. Application scenarios

Underwater applications can be classified as follows. We distinguish between (Heidemann et al., 2012) (1) *scientific*, (2) *industrial*, (3) *military and home security applications*. *Scientific applications* are related to the observation of the environment, that is, the monitoring of geological processes on the ocean floor, water characteristics and marine life. *Industrial applications* monitor and control commercial activities. Finally, *military and home security applications* involve securing port facilities or ships in foreign harbors, de-mining and communication with submarines and divers. Next, several application scenarios that benefit from the IoUT to gain an insight into integration issues are introduced. We focus on one *scientific application* (aquarium), two *industrial applications* (fish farms and pipeline monitoring) and one *military and home security application* (harbor security).

4.1. Aquarium

Fish tagging in aquariums (see Fig. 2) with PIT tags using RFID enables that visitors learn fish characteristics in real-time. The tag readers located above the exhibition tank emit radio waves. Every time a tagged fish swims within range of a reader, it sends its unique Identifier (ID) string towards the reader, which forwards it to the RFID server. Users can also detect this ID with the aid of a reader embedded in a monitoring station (smartphone), as shown in Fig. 2. Fish specific information is returned from the RFID database to the touch screen of a computer next to the aquarium. The species' name, origin, diet and other individual characteristics of the fish (age, weight) are displayed as users navigate through the menus. Instructive videos can also be stored and downloaded from a multimedia server. They can be downloaded together with all fish data at the monitoring stations. This system is also an accurate way for aquarium keepers to track the individual medical history and treatment record of every fish in the tank. Fish reports/statistics are sent periodically from the monitoring

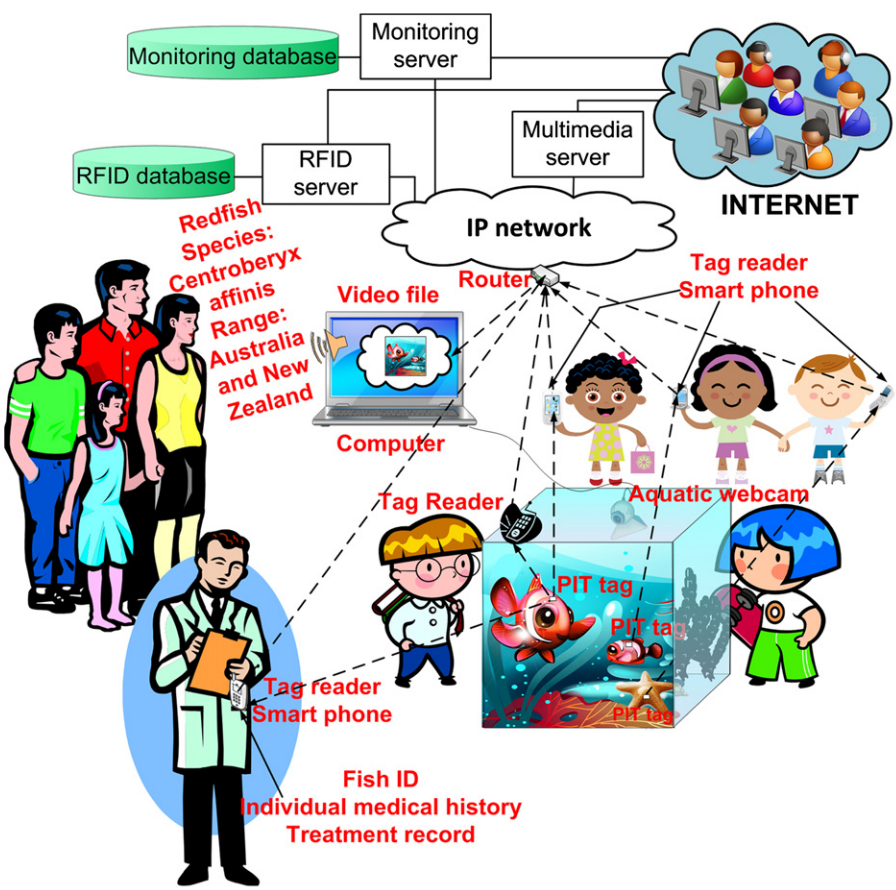

Fig. 2. Aquarium scenario.

server to the monitoring station of the aquarium keepers. On the other hand, images or video of the fish in the aquarium are streamed from underwater webcams over the Internet in real-time. These webcams are underwater 'objects' that automatically distribute pictures/videos for animal lovers via social networks.

Singapore's Underwater World aquarium implemented the world's first RFID system for a sea exhibition in 2007. Low frequency 23 mm glass encapsulated PIT tags were inserted under the skin of the fish. An innovative antenna design mounted on the viewing window identified the tagged fish underwater up to half a meter away. Information concerning the fish was displayed on a touch-screen.

4.2. Fish farms

Fish farming (see Fig. 3) is the process of raising fish in an enclosed area, usually for food.

A radio tag is placed on each fish. A unique code identifies it. The fish farms employees have a monitoring station (smartphone) that scans radio tags. It is also possible to set receivers in the tanks/ponds, which receive the tag ID string and forward it towards the monitoring station using Bluetooth or ZigBee. Later it is sent from the monitoring station to the radio server. The radio database records fish information such as species, producing area, water condition, farming time, origin of the larva and daily activities of feeding and drugging until the fish becomes fully mature. This information is associated with the fish identification number of the radio tag. After querying the database, a detailed fish report is displayed on the monitoring station of the employee. This data is very useful when the fish are sold and shipped.

It is important to identify individual fish. This way, general information (species name and habitat) in the radio database of fish is complemented with specific details about them such as when and where they were collected, their sex, age, body length, weight, and growth history. These specific details are important to track the individual medical history and treatment record of every fish, which is indispensable to carry out real-time control of fish and ensure food safety. Radio tags are expensive, since they run between \$200 and \$500, depending on their features. If a cheaper solution is required, they can be replaced by PIT tags in the fish farms. PIT tags have a more limited detection range (approximately 20 cm instead of 10 m in freshwater), but are also much cheaper (about \$3 each). In any case, radio tags should be replaced by PIT tags later before fish are shipped from the fish farms to the buyer. All fish data can be directly written in the PIT tags using RFID.

Furthermore, the *water quality* of the fish farms needs to be *monitored*, since it is vulnerable to the agricultural use of pesticides, fertilizers and pollution. Underwater sensors (see Fig. 3) sense water quality variables such as water temperature, dissolved oxygen concentration, pH value and electrical conductivity (salinity) (Zhu et al., 2010). The sensed real-time data is transmitted to the surface sink, which forwards it to the water quality monitoring server. This server analyzes this data and warns stakeholders with text or audio messages sent to their monitoring stations in case of anomalous values. For instance, dissolved oxygen is a good indicator of water quality status if the predefined acceptable limits are not reached. The water quality database stores the parameter values including abnormal ones. Stakeholders get these values in real-time using their monitoring stations, obtain complete data analysis reports and are aware of alarms in specific tanks/ponds.

In Zhu et al. (2010), a remote wireless monitoring system that uses wireless communication technology to provide water-quality information for intensive aquaculture in China is introduced. Artificial neural networks are used to create a non-linear predictive model of the system to forecast water quality based on historical data. This way, the dynamic trend of the water quality parameters (such as dissolved oxygen) at different monitoring sites is also provided.

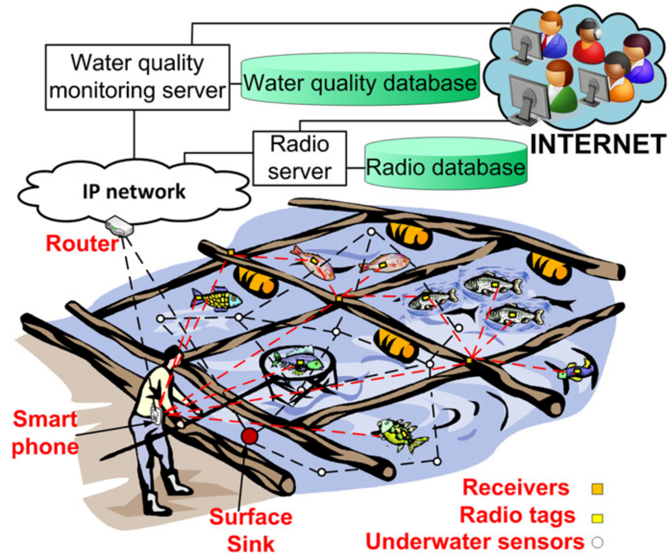

Fig. 3. Fish farm scenario.

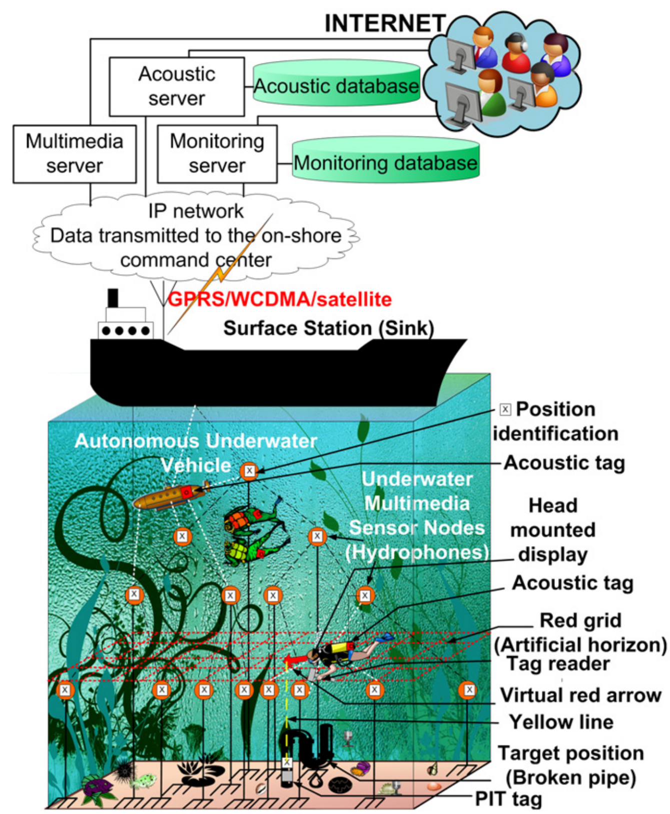

Fig. 4. Marine environment. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

4.3. Pipeline monitoring

Underwater sensors and AUVs integrate for an efficient inspection of *underwater marine infrastructure* (see Fig. 4), e.g. for control and detection of oil spill at pipelines.

Sensors can be located both inside and outside the pipelines. Underwater sensors located outside pipelines are placed at fixed positions (anchored to the sea bottom and floating at different depths) or float freely with water currents. Localization techniques (Erol-Kantarci et al., 2010) are required to know their positions. Other sensors placed inside the pipelines measure the pressure and the speed of the oil, as well as the acoustic vibrations caused by the leakages. The data collected by sensors is transmitted through the sensor network towards the sink, which forwards it to the onshore monitoring center.

AUVs move through the monitoring zone and communicate with underwater sensors through acoustic links to also gather all this data. Hydrophones (acoustic sensors) can be used to track the 3-D position of AUVs (carrying acoustic tags); it is computed by the acoustic server at the monitoring center.

AUVs collect information, examine and catalog natural habitats, inspect (and potentially repair) marine infrastructure (e.g. oil pipelines). Underwater sensors can signpost the area where repairs are needed. PIT tags can be attached to an underwater oil pipeline to pinpoint more accurately where to do repairs. The Gulmar Offshore Group, a pipeline maintenance company, has developed a pipe tracking system consisting of PIT tags located at 48-m intervals along the outside of the pipe and protected with a plastic housing. Divers use handheld interrogators to read a tag and write information during maintenance operations (see Fig. 4). AUVs can also carry tag readers.

In addition, underwater multimedia acoustic sensor networks (Pompili and Akyildiz, 2010) enable picture and video acquisition and classification. These videos and images are sent to the multimedia server; this way, stakeholders can stream and watch them. Multimedia content is very useful in disaster prevention to detect and analyze outliers in the monitoring area. It can also serve as support information during inspection and repair tasks.

Although AUVs are an excellent aid for endurance underwater missions, divers are still required for certain underwater operations due to their superior mental and manual capabilities to perform complex tasks such as underwater construction, that is, the process of building and assembling marine structures. Some examples are pipeline projects (rerouting, abandonment and repair) and hot tapping (the connection of a new pipeline while the pipeline remains in service) (Morales et al., 2009). However, divers can suffer stress. Their integrity is exposed to harsh underwater conditions such as high pressure, visual perception difficulties, weightlessness, currents, etc. Those factors cause a restriction in divers' sensory inputs, cognition and memory.

In Morales et al. (2009), an Underwater Augmented Reality (UWAR) system is introduced to assist divers in locating the work site to perform repairs and in maintaining constantly their position. The system (see Fig. 4) consists of a video see-through Head Mounted Display (HMD) with a webcam in front of it, protected by a custom waterproof housing placed over the diving mask. Optical square-markers are used for positioning and orientation tracking purposes such as identification of the work site. The tracking was implemented with software. Augmented Reality (AR) incorporates virtual elements (environmental and task information) in the divers' view to improve the visual cues and the surroundings understanding. The visualization of an artificial horizon (red grid) (see Fig. 4) increases the position awareness of the divers within their environment and work-site. Navigation aids consist of guidance to the work-site implemented with a virtual red arrow sign pointing to the task location. A yellow line links the arrow with the target position (work site). The divers' position is tracked. Acoustic tags transmit a ping with identification information about the tagged diver to underwater sensors (hydrophones). By determining the sound's time of arrival at multiple hydrophones, the 3D position of the diver is calculated at the acoustic server using the acoustic database. The diver's location is forwarded back to the diver using the sensor network. Using this method his/her position and the position of other divers is known by the diver even if visual contact is lost. A wrist-worn computer can also be used by a diver to obtain his/her depth with good visibility conditions. Multi-User Long Base Line (MULBL) is another underwater acoustic tracking system for divers (Newborough and Woodward, 1999). Information concerning the location of other divers, underwater sensors and AUVs is displayed in real-time as 3-D graphical elements (AR) through the HMD of the diver. Acoustic phones or modems that enable divers to send text messages are some examples of underwater objects to keep contact between divers and with the outside world.

4.4. Harbor security

Underwater sensor networks together with underwater and surface vehicles can contribute to protect harbors (see Fig. 5). The mobile security network is formed by ASVs, AUVs, airplanes and satellites. Stationary platforms that contain buoys and sea-mounted equipment are also included (Patrikalakis et al., 2010). A large variety of sensors can be mounted on the vehicles.

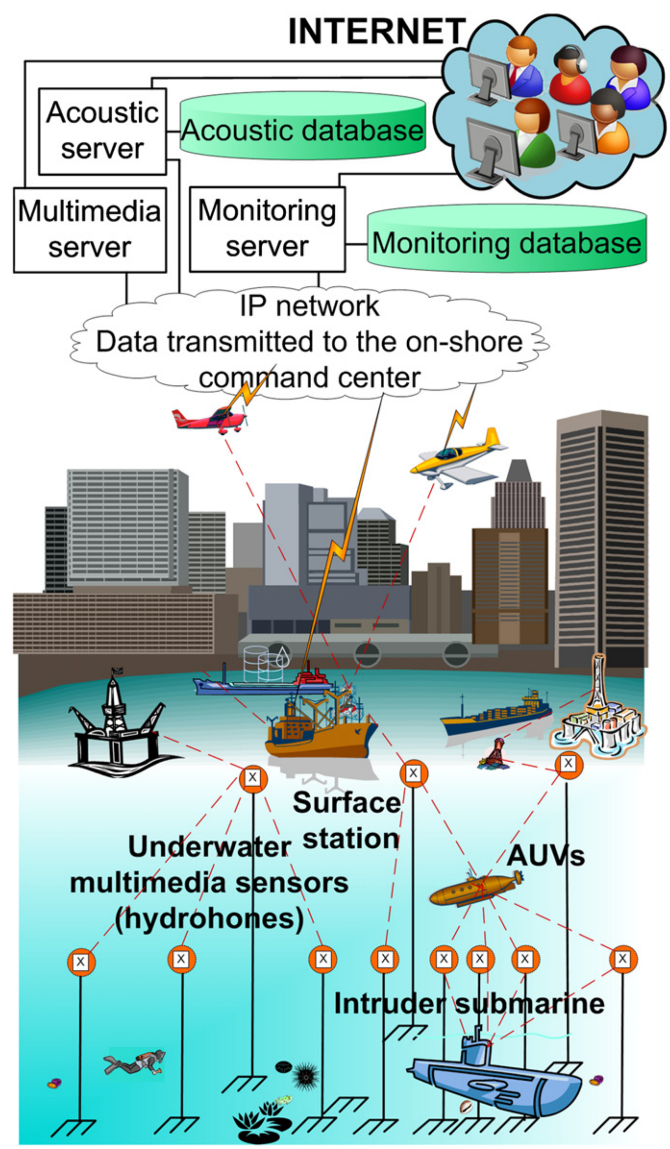

Fig. 5. Harbor security scenario.

Another certain number of underwater sensors are deployed to cover a large volume of water.

Metal pieces at the seabed and thin ropes are used to attach these sensor nodes and distribute them at different depths (Akyildiz et al., 2005) to collect information about different events. This deployment strategy requires building a tree-like hierarchical multi-hop routing topology. The sensed data is sent to the surface station (sink), which floats on the water surface and uses long distance radio communication to send this data to an onshore station directly or through airplanes. Further analysis of the data is performed at the onshore station. These underwater sensors can search for intruder submarines and send alert messages to AUVs in case of detection. In Barr et al. (2011), an energy-conserving approach to detect intruding submarines is described. It consists of a 3-dimensional area of mobile acoustic or magnetic sensors. Each sensor is placed in a grid position trying to minimize the amount of energy spent on sensor movement. In Chung et al. (2011), the periodic trajectories that AUVs must trace out to maximize the probability of detection of an underwater intruder are determined.

Light Detection And Ranging (LIDAR) is an optical remote sensing technology that can measure the distance to, or other properties of a target by illuminating the target with light, often using pulses from a laser. LIDAR sensors mounted on ASVs can be used to survey ships incoming to a port for explosives or illegal items attached to the exterior of the ship (Patrikalakis et al., 2010). Images of suspicious underwater objects such as mines should also be recognized and transmitted quickly to a command center. Novel underwater laser imaging networks are also being developed. Laser imaging and communication technologies can be distributed within a group of small co-operating robots. This way, images of suspicious underwater objects would be quickly transmitted to the command center.

Video and images detected by underwater robots as well and multimedia acoustic sensor networks are sent to the multimedia server. Multimedia content is very useful in coastal and tactical surveillance.

5. Benefits of the IoUT

Next, the benefits of the IoUT are discussed. We focus on the benefits of applying the IoUT in the application scenarios described in the previous section.

Currently, aquarium visitors observe fish as they swim in tanks. They can read the fish facts and information on the screens or walls and watch videos about marine animals. Nevertheless, the IoUT offers visitors (especially children) a more interactive, exciting and educational experience. Now a fish can be identified in real-time and individually. Apart from general information on the fish's species, habitat and range, additional details about that specific fish are displayed including details about when and where it was collected, its age, weight, growth history and even its nickname. Watching aquatic animals in real-time and complementing it in situ with multimedia content is a very effective way to get people closer to the animals and connect with their histories to improve the learning experience. In addition, the IoUT facilitates that aquarium keepers monitor the individual health of each animal and understand better its life-span and behavior.

On the other hand, the IoUT in fish farms is also a powerful tool for fish control to ensure food safety. The fishery products supply chain involves five different steps (Bin and Chen, 2009): production, transportation, processing, storage and distribution. Barcodes are the most common labeling method to enable traceability. The barcodes EAN-13 and UCC-12 codes (European Article Number and Uniform Code Council) are the most used. However, PIT tags (implantable RFID devices) have many advantages compared to barcodes such as reprogrammability, ability to contain more product information and ability to read without line-of-sight reading (Narasimhan, 2006). In addition, at present only very few small companies have developed their own systems for internal traceability (internal tracing in one of the steps of the chain). They often use ineffective manual data handling in their internal business processes (Trebar et al., 2011), which cannot be applied in the data exchange between partners in the fish supply chain. For all these reasons, radio and RFID technology can help to carry out real-time control of fishery products, to ensure the quality control and store additional information at each stage. An appropriate control of the water quality to keep the concentration of water environmental parameters in the optimal range is essential to preserve fish farms. In most of the aquaculture industries, traditional methods are employed to assess the water quality of the ponds/tanks. Ponds/tanks are inspected and water samples are taken to detect hazardous substances. These samples are analyzed in a chemical laboratory. The main part of the process is manual, requires frequent visits to the water location and is time-consuming. Therefore, real-time *water quality monitoring* on a regular basis using wireless sensors is an effective way to detect and reduce large-scale fish diseases earlier, and enhance the fish growth rate.

Furthermore, the pipeline monitoring system prevents/warns about possible damages. Pipeline monitoring has often been restricted to visual inspection and mass/volume balance measurements. As a result, pipeline failures are usually noticed too late after the surrounding environment has been severely damaged. Currently, AUVs cooperate on the inspection of marine infrastructure. However, these visual inspections are expensive and only capable to detect external anomalies and not internal structural deterioration. Therefore, the integration of RFID and sensor technology is very useful to quickly identify problems and pinpoint, in real-time, disruption and damage in underwater pipelines. In addition, scuba divers are commonly in charge of complex tasks during pipeline repair operations. Since the IoUT provides context-awareness, they can reduce their stress levels and perform their tasks more safely and effectively.

Finally, harbor security is essential to maintain trade and growth in a region. The IoUT is the key to sustain a safe harbor environment, which is crucial for the shipping industry and the economic growth of a country. At present, ASVs, AUVs, buoys, and emplaced sensor systems and networks are able to secure harbors against maritime threats. However, many ports still lack any existing security systems. In addition, more flexible, sophisticated and powerful systems need to be developed. For instance, scene awareness would play a major role in automated anomaly detection. More varied sensors and data such as from airborne and satellite sources may be added. A sophisticated coastal security system consisting of cameras and different kinds of sensors could track a vessel from the moment it leaves a foreign port on its way to the protected harbor. The combination of database knowledge with real-time sensor input would be very effective to monitor ship traffic and alert of potential security risks.

6. Research challenges

Next, the research challenges concerning the IoUT are introduced.

A significant challenge to the IoUT is *self-management*. It refers to the process by which the IoUT manages its own operation without human intervention. For this purpose, support for *self-configuration*, *self-healing*, *self-optimization* and *self-protection* capabilities is required (Haller et al., 2009). *Self-configuration* is related to the automatic configuration of components; *self-configuration* capabilities are crucial to coordinate operations between underwater sensors and AUVs by exchanging configuration, location and movement information. *Self-healing* handles the automatic discovery and correction of faults; it is particularly challenging in the IoUT due to underwater channel fluctuations and device mobility. Underwater communication is seriously limited by the harsh conditions of the underwater channel (high and variable propagation delays and multipath), which combined with other negative effects of the underwater acoustic medium such as very high attenuation and Doppler distortion (Stojanovic, 2007), result in high bit error rates. In the extreme cases, shadow zones are formed. They are time-variant areas where there is little or no signal propagation due to the refraction of signals by variations of the speed of sound based on depth (Preisig, 2007). This underwater propagation phenomenon causes connectivity interruptions. In addition, underwater devices are prone to failures due to fouling. Therefore, periodical cleaning mechanisms against corrosion and efficient fault-tolerant algorithms are required. Since shadow zones represent a serious obstacle for communication in the IoUT, efficient mechanisms to detect and re-establish communication under the presence of shadow zones should be developed. An adaptive topology reorganization scheme is proposed in Domingo (2009) to maintain connectivity in multi-hop underwater wireless sensor networks affected by shadow zones. *Self-optimization* focuses on the automatic monitoring and control of resources to ensure the optimal functioning with respect to the defined requirements; IoUT devices should autonomously learn application-specific information during the course of their operations with the aid of tags and sensors to *self-optimize* the system performance. Finally, *self-protection* tackles the proactive identification and protection from arbitrary attacks. Wireless underwater channels can be eavesdropped on Domingo (2011). Attackers may intercept the information transmitted and attempt to modify or drop packets. Malicious nodes can create out-of-band connections via fast radio (above the water surface) and wired links which are referred to as wormholes (Domingo, 2011). Since sensors are mobile, their relative distances vary with time. The dynamic topology of underwater sensor networks not only facilitates the creation of wormholes but it also complicates their detection (Wang et al., 2008). Consequently, there is a need to develop new techniques against wormholes, and improve existing ones.

Another important challenge is *the improvement of tracking techniques*. Since in the IoUT they are commonly applied to alive animals, it must be carefully studied whether the resulting tags harm animals or obstruct their activity, which is the suitable shape and size of these tags or what the tags are made of. Sedation methods should also be studied (Neiffer and Stamper, 2009). Safe and effective sedatives or anesthetics are crucial in fish farming and fish management activities for procedures that may cause more than momentary or slight pain or distress. In addition, the impact of acoustic communication on marine mammals is another important concern related to the protection of animals.

Energy efficiency is very challenging in machine-to-machine networks architectures (Tekbiyik and Uysal-Biyikoglu, 2011). Underwater communication systems have more stringent power requirements than terrestrial systems (Akyildiz et al., 2005) because acoustic communications are more power-hungry, and typical transmission distances in the IoUT are greater; hence, higher transmit power is required to ensure coverage. Topology optimization methods should be designed for the IoUT, since network topology is decisive in determining the energy consumption. In addition, long-term non-time-critical monitoring applications (Cui et al., 2006) (oceanography, marine biology, pollution detection, and oil/gas field monitoring) require that nodes operate for long periods (years or decades) after they are deployed and batteries are difficult to replace/recharge. Using energy harvesting as secondary energy source to supplement batteries does not eliminate the problem of having to replace the batteries when they run out (Seah et al., 2009). Harvested energy should be used as the only energy source. Supercapacitors can replace batteries to store the harvested energy, since they can be recharged millions of times and have a higher energy density. Combining low-power electronics, energy harvesting devices, and supercapacitors, it is feasible to implement IoUT devices that rely only on *energy harvesting* to operate. Powerful *underwater energy harvesting techniques* able to power IoUT devices are required.

Communications coverage should be guaranteed although the 'objects' of the IoUT are sparsely deployed because of the cost of underwater hardware. The IoUT can be easily partitioned due to scattered deployment and node mobility. AUVs can be used as temporary relay nodes to restore connectivity. Multi-hop routing is used to maintain communication in large underwater areas. DTN techniques are required to maintain routing. Disruption tolerant techniques that satisfy different application requirements (Guo et al., 2008) even with no stable connectivity are needed (Zorzi et al., 2010).

Standardization is also very important. The development of architectures and solutions for the IoUT is also needed to address interoperability between heterogeneous underwater systems, where no de jure or de facto standard currently exists. Global standards should be created to avoid the *interoperability* problem. *The heterogeneity of devices*, *technologies and services* is very challenging. Although at the present time basically only AUVs, sensors, divers and tracked animals are interconnected, the heterogeneity of aquatic linked devices is expected to increase with the technological evolution of the IoUT. The requirements of applications (e.g. short-term time-critical aquatic exploration and long-term non-time-critical aquatic monitoring) are very different in terms of latency, reliability, etc. New protocols that provide interoperability between heterogeneous underwater 'objects' should be designed. It is also required to develop gateways for protocol conversion to enable communication between the underwater domain and above-water IP-based networks. They should guarantee the functioning of existing services and applications in very different media (acoustic and radio/satellite) via an intelligent adaptation. Finally, we envision that the evolution of the IoUT in the following years will make necessary to create a global standard that is adapted to the limited characteristics of the underwater channel and offers internet connectivity to a larger number of low-power devices with limited processing capabilities in a similar way the 6LoWPAN (Shelby and Bormann, 2009) does in the IoT. The existence of a single Internet Protocol (IP)-based network will eliminate the need of gateways for protocol conversion.

The aquatic environment is particularly vulnerable to *malicious attacks* due to the high bit error rates, the large and variable propagation delays, and the low bandwidth of acoustic channels. The link quality in underwater communication is severely affected by multipath, fading and the refractive properties of the sound channel. As a result, the bit error rates of acoustic links are often high and losses of connectivity arise. High bit error rates cause packet errors. Consequently, critical security packets can be lost (Domingo, 2011). In addition, since power consumption in underwater communications is higher than in terrestrial radio communications and given that the underwater sensors are sparsely deployed, energy exhaustion attacks to drain the batteries of nodes pose a serious threat for the network lifetime. The unique characteristics of the underwater acoustic communication channel (Domingo, 2011) require the development of efficient and reliable security mechanisms for the IoUT. Inter-vehicle and sensor-AUV communications should be protected against denial-of-service (DoS) attacks, which prevent the IoUT from functioning correctly or in a timely manner.

Cooperation is also indispensable. Scenarios where more capable nodes (AUVs or handheld monitoring stations) discover other resource-restricted nodes, synchronize with one another and help each other in reliable data delivery seem very promising. In the course of time more direct thing-to-thing connections (between 'things' that are currently considered resource-restricted) will be established as communication, processing capabilities, technologies deployed for web services and energy harvesting techniques evolve.

Finally, the cross-layer interactions between circuit design, energy harvesting, communications, and networking should be analyzed. A joint cross-layer optimization of different network functionalities (e.g. physical layer, MAC layer and routing) is necessary to support the heterogeneity of IoUT 'objects' and the different requirements of long-term non-time-critical and short-term time-critical applications. Since MAC and routing solutions are closely related to the challenging underwater channel and its limitations, a distributed cross-layer communication solution that enables multiple devices to efficiently and fairly share the underwater acoustic medium is needed (Pompili and Akyildiz, 2010). This issue is especially important to enable effective networking between devices with severe power constraints, thus prolonging the lifetime of the network.

7. Conclusion

In this paper, the IoUT is introduced. Its different characteristics, relevant application scenarios and main benefits have been described. The research challenges have also been surveyed. They remain wide open for future investigation.

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