12

Common Framework Model for Multi-Purpose Underwater Data Collection Devices Deployed with Remotely Operated Vehicles

M.C. Caraivan[1], V. Dache[2] and V. Sgarciu[2]

[1]Faculty of Applied Sciences and Engineering, University Ovidius
of Constanta, Romania
[2]Faculty of Automatic Control and Computers, University Politehnica
of Bucharest, Romania
Corresponding author: M.C. Caraivan <caraivanmitrut@gmail.com>

Abstract

This paper is following the development of real-time applications for marine operations focusing on modern modelling and simulation methods and presents a common framework model for multi-purpose underwater sensors used for offshore exploration. It is addressing deployment challenges of underwater sensor networks called by the authors "Safe-Nets" by using Remotely Operated Vehicles (ROV).

Keywords: Remotely Operated Vehicles, ROV, simulation, testing, object modelling, underwater component, oceanographic data collection, pollution.

12.1 Introduction

The natural disaster following the explosion of BP Deepwater Horizon offshore oil-drilling rig in the Gulf of Mexico has raised questions more than ever about the safety of mankind's offshore oil-quests. For three months in 2010, almost 5 million barrels of crude oil formed the largest accidental

Advances in Intelligent Robotics and Collaborative Automation, 257–294.

marine oil spill in the history of the petroleum industry. The frequency of maritime disasters and their effects appear to have dramatically increased during the last century [1], and this draws considerable attention from decision makers in communities and governments. Disaster management requires the collaboration of several management organizations resulting in heterogeneous systems. Interoperability of these systems is fundamental in order to assure effective collaboration between different organizations.

Research efforts in the exploration of offshore resources have increased more and more during the last decades, thus contributing to greater global interest in the area of underwater technologies. Underwater sensor networks are going to become in the nearby future the background infrastructure for applications which will enable geological prospection, pollution monitoring, and oceanographic data collection. Furthermore, these data collection networks could in fact improve offshore exploration control by replacing the on-site instrumentation data systems used today in the oil-industry nearby well heads or in well-control operations, e.g. using underwater webcams which can provide important visual data aid for surveys or for offshore drilling explorations. These facts lead to the idea of deploying multi-purpose underwater sensor networks along-side with oil companies' offshore operations. The study is trying to show the collateral benefits of deploying such underwater sensor networks and we address state-of-the-art ideas and possible implementations of different applications like military surveillance of coastal areas, assisting navigation [2] or disaster prevention systems – including earthquakes and tsunami detection warning alarms in advance – all in order to overcome the biggest challenge of development: the cost of implementation.

It is instructive to compare current terrestrial sensor network practices to underwater approaches: terrestrial networks emphasize low-cost nodes (around a maximum of US\$100), dense deployments (at most a few 100m apart) and multi-hop short-range communication. By comparison, typical underwater wireless communications today are expensive (US\$10.000 per node or even more), sparsely deployed (a few nodes, placed kilometres apart), typically communicating directly to a "base-station" over long-distance ranges rather than with each other. We seek to reverse the design points which make land networks so practical and easy to expand and develop, so underwater sensor nodes that can be inexpensive, densely deployed, and communicating peer-to-peer [3].

Multiple Unmanned or Autonomous Underwater Vehicles (UUVs, AUVs), equipped with underwater sensors, will also find application in exploration of natural undersea resources and gathering of scientific data in collaborative monitoring missions. To make these applications viable, there is a need to enable underwater communications among underwater devices. Ocean Sampling Networks have been experimented in the Monterey Bay area, where networks of sensors and AUVs, such as the Odyssey-class AUVs, performed synoptic, cooperative adaptive sampling of the 3D coastal ocean environment [4]. While offshore constructions' number grows, we should be able to implement auxiliary systems that allow us to better understand and protect the ocean surface we are building on. We will be using Remotely Operated Vehicles (ROVs) and a VMAX-Perry Slingsby ROV Simulator with scenario development capabilities to determine the most efficient way of deploying our underwater sensor networks, which we called "Safe-Nets", around offshore oil drilling operations, including all types of jackets, jack-ups, platforms, spars or any other offshore metallic or concrete structure.

The ability to have small devices physically distributed near offshore oil-fields' operations brings new opportunities to observe and monitor micro-habitats [5], structural monitoring [6] or wide-area environmental systems [7]. We even began to imagine a scenario where we can expand these sensor networks in order to slowly and steadily develop a global "WaterNet", which could be an extension of the Internet on land. In the same manner which allowed Internet networks on land to develop by constantly adding more and more nodes to the network, we could allow information to be transmitted from buoy to buoy in an access-point like system. These small underwater "Safe-Nets" could be joined together and the network could expand into a global "Water-Net" in the future, allowing data to be sent and received to and from shore bases. Of course, today, we can see considerable less kilobytes of data to be sent and received at first, but the main advantages would be in favour of disaster prevention systems. "Safe-Nets" for seismic activity and tsunami warning systems alone can represent one of the reasons for underwater network deployment, which are quite limited today compared to their counterparts on land. We propose a model of interoperability in case of a marine pollution disaster for a management system based upon Enterprise Architecture Principles.

If we keep in mind that the sea is a harsh environment, where reliability, redundancy and maintenance-free equipment are most desirable objectives, we should seek the methods and procedures for keeping the future development in a framework that should be backwards compatible with any other sensor nodes already deployed. In order to comply with the active need for upgrading to future technologies, we have thought of a common framework model with multiple layers and drawers for components which can be used for different purposes, but mainly for underwater data collection and monitoring. This development using Enterprise Architecture Principles is sustainable through time, as it is backed up by different solutions to our research challenges, such as power supply problem, fouling corrosion, self-configuration, self-troubleshooting protocols, communication protocols and hardware methods.

Two-thirds of the surface of Earth is covered by water and as history proved it, there is a constantly increasing number of ideas to use this space. One of the most recent is perhaps moving entire buildings of servers - Google's Data-Centres [8] overseas, literally, because of their cooling needs which nowadays are tremendous. These produce a heat footprint clearly visible even from satellites and by transferring them to the offshore environment, their overheating problems would have cheaper cooling methods which could be satisfied by the ocean's seawater almost constant temperature. Also, we discuss the electrical power supply possibilities further in the following chapter.

12.2 Research Challenges

We seek to overcome each of the design challenges that prohibited underwater sensor network development, especially by designing a common framework with different option modules available to be installed. If having a hardwire link at hand, by attaching these devices to offshore construction sites or to autonomous buoys, we could provide inexpensive sensors by using the power supply or communication means from that specific structure. We are looking forward to develop a variety of option modules for our common framework to be used for all types of underwater operations, which can include the instrumentation necessities nearby wellheads and drill strings or any type of oceanographic data collection, therefore becoming a solution at hand for any given task. This could provide the financial means of deploying underwater Safe-Nets, especially by tethering to all the offshore structures or exploration facilities which need different underwater data collection by their default nature.

12.2.1 Power Supply

Until now, only battery power was mainly used in underwater-based sensor deployments. The sensors were deployed and shortly afterwards were recovered. In our case, the close proximity to oil-rig platforms or other offshore constructions means already existing external power sources: diesel or gas generators, wind turbines, gas pressure turbines. We can overcome this design issue with cable connections to jackets or to autonomous buoys with solar panels which are currently undergoing research [9, 10].

Industrial applications such as oil-fields and production lines use extensive instrumentation, sometimes with the need of a video-feedback from the underwater operations site. Considering the depths at which these cameras should operate, there is also an imperative need for proper lighting of the area; therefore we can anticipate that these nodes will be tethered in order to have a power source at hand.

Battery power problems which in our case can be overcome not only by sleep-awake energy efficient protocols [11–13], but also by having connectivity at hand to other future system types of producing electricity from renewable resources, like wave energy converter units according to the European project Aquatic Renewable Energy Technologies (Aqua-RET) [14]:

- Attenuator-type Figure 12.1: Pelamis Wave Energy Converter [15];
- Axial symmetric absorption points as in Figure 12.2: WaveBob [16], AquaBuoy, OE Buoys [17] or Powerbuoy [18];
- Wave-level oscillation converters: completely submerged Waveroller or surface Oyster [19];
- Overtopping devices Figure 12.3: Wave Dragon [20];

Figure 12.1 Pelamis wave converter Orkney, U.K.

- Submersible differential pressure devices Figure 12.4: Archimedes Waveswing [21];
- Oscillating Water Column (OWC) devices.

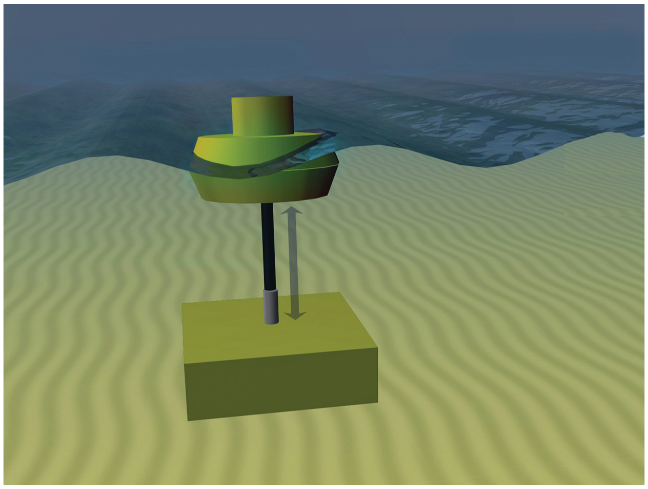


Figure 12.2 Axial symmetric absorption buoy.

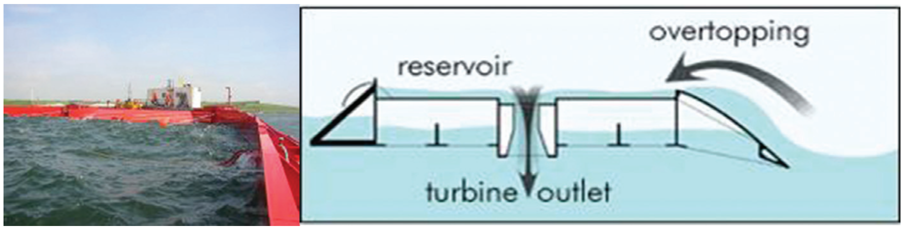


Figure 12.3 Wave Dragon - Overtopping devices principle.

Figure 12.4 Archimedes Waveswing (AWS).

Figure 12.5 Wind farms in North Sea.

In addition, we are considering also other types of clean energy technology production systems at sea:

- Wind farms: usually the wind speed at sea is far greater than on land, however, by comparison to its land counterpart, offshore wind turbines are harder to install and need more technical and financial efforts. The distance to land, water depth and sea floor structure are factors that need to be taken into consideration for Aeolian projects at sea. The first project for an offshore wind farm was developed in Denmark in 1991;
- Oceans' thermic energy by using the temperature difference between surface and depth waters, which needs to be at least 20°C at less than 100m from sea surface. These desiderates are usually full-filled nearby in Equatorial regions;
- Tidal waves and ocean currents such as Gulf Stream, Florida Straits, North Atlantic Drift possess energy which can be extracted with underwater turbines.

Besides the power supply facilities, all these devices themselves could in fact be areas of interest for deployment of our Safe-Net sensors.

12.2.2 Communications

Until now, there were several attempts to deploy underwater sensors that record data during their mission, but they were always recovered afterwards. This did not give the flexibility needed for real-time monitoring situations like surveillance or environmental and seismic monitoring. The recorded data could not be accessed until the instruments were recovered. It was also impossible to detect failures before the retrieval and this could easily lead to the complete failure of a mission. Also, the amount of data stored was limited by the capacity of the devices on-board the sensors (flash memories, hard disks).

Two possible implementations are buoys with high-speed RF-based communications, or wired connections to some sensor nodes. The communication bandwidth can be provided also by satellite connections which are usually present on offshore facilities. If linked to an autonomous buoy, the device provides GPS telemetry and has communication capabilities of its own. Therefore, once the information gets to the surface, radio communications are considered to be already provided as standard. Regarding underwater communications, usually the typical physical layer technology implies acoustic communications. Radio waves have long-distance propagation issues through sea water and can only be done at extra low frequencies, below 300 Hz [22]. This requires large antennae and high transmissions power, which we would prefer avoiding. Optical waves do not suffer from such high attenuation but are affected by scattering. Moreover, transmission of optical signals requires high precision in pointing the narrow laser beams. The primary advantage of this type of data transmission is the higher theoretical rate of transmission, while the disadvantages are the range and the line-of-sight operation needed. We did not consider this as a feasible solution due to marine snow, non-uniform illumination issues and other possible interferences.

We do not intend to mix different communication protocols with different physical layers, but we analyze the compatibility of each with existing underwater acoustic communications, state-of-the-art protocols and routing algorithms. Our approach will be a hybrid system, like the one in Figure 12.6 that will incorporate both tethered sensors and wireless acoustic where absolutely no other solution can be implemented (e.g.: a group of bottom sea floor anchored sensor nodes are implemented nearby an oil pipe, interconnected to one or more underwater "sinks", which are in charge of relaying data from the ocean bottom network the a surface station [23].

Regarding the propagation of acoustic waves in the frequency gamma we are interested in, for the multi-level communication between Safe-Net sensor nodes, we are looking into already known models [24]. One of the major problems related to the fluid dynamics are the non-linear movement equations, which imply the fact that there isn't a general exact solution. Acoustics represent the first order of approximation in which the non-linear

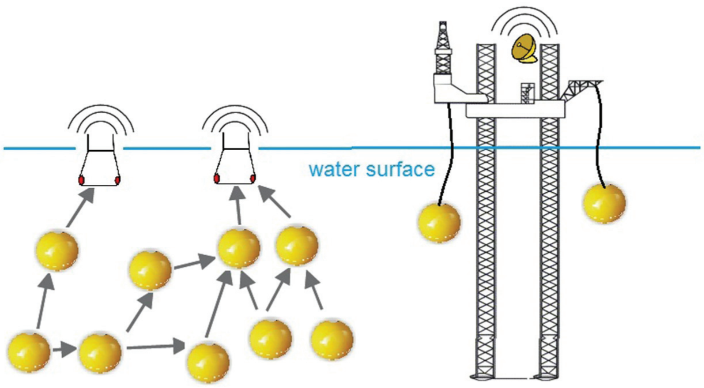


Figure 12.6 Possible underwater sensor network deployment nearby Jack-up rig.

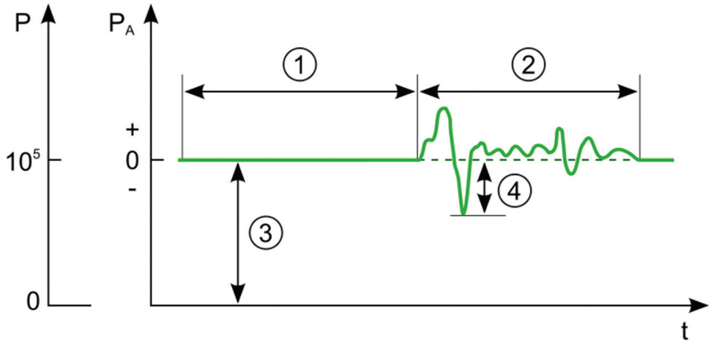


Figure 12.7 Sound pressure diagram: 1– Equilibrium; 2– Sound; 3– Environment Pressure; 4– Instantaneous Pressure of Sound.

effects are neglected [25]. Acoustic waves propagate because of the medium compressibility and the acoustic pressure or the sound pressure represents the local deviation of the pressure whose root cause can be traced back to a sound wave generated against the local environment. In air, the sound pressure can be measured using a microphone, while in water it can be measured using a hydrophone.

Considering the case of acoustic waves propagation in real fluids for our mathematic general formalism, we have made the following assumptions: gravity forces can be neglected, so equilibrium pressure and density get uniform values all over the fluid's volume (p_0 and ρ_0); the dissipative effects such as viscosity and thermic conductibility are negligible; the medium is homogenous, isotropic and has perfect elasticity, as well as the fluid particles speed is slow (the “*small amplitudes*” assumption). Therefore, we can write a Taylor development for the pressure and density fluctuation relationship:

$$\mathrm{p} = p_0 + \frac{\partial p}{\partial \rho}|_{\rho\,=\,\rho_0}\,(\rho - \rho_0) + \frac{1}{2}\frac{\partial^2 p}{\partial \rho^2}|_{\rho\,=\,\rho_0}\,(\rho - \rho_0)^2 + \ldots, \tag{12.1}$$

where the partial derivatives are constant for the adiabatic process around the ρ_0 equilibrium density of the fluid.

If the density fluctuations are small, meaning $\bar{\rho} \ll \rho_0$, then the high-order terms can be reduced and the adiabatic state equation becomes linear:

$$\mathrm{p} - p_0 = K\frac{\rho - \rho_0}{\rho_0}. \tag{12.2}$$

The pressure generated by the sound *p* (12.4) is directly related with the particle movement and the amplitude ξ through equation (12.3):

$$\xi = \frac{v}{2\pi f} = \frac{v}{\omega} = \frac{p}{Z\omega} = \frac{p}{2\pi f Z}, \tag{12.3}$$

$$\mathrm{p} = \rho\mathrm{c}2\pi\mathrm{f}\ \xi = \rho\mathrm{c}\omega\xi = \mathrm{Z}\omega\xi = 2\pi\mathrm{f}\xi\mathrm{Z} = \frac{aZ}{\omega} = Zv = c\sqrt{\rho E} = \sqrt{\frac{P_{ac}Z}{A}}, \tag{12.4}$$

where the symbols together with the I.S. measurement units are presented in the following table:

The fundamental attenuation describes the power loss of a tone at a frequency *f*, during its movement across a distance *d*. The first level of our

Table 12.1 Symbols Definition and Corresponding I.S. Measurement Units

Symbol	Measurement Unit	Description
p	Pascal	Sound Pressure
f	Hertz	Frequency
ρ	kg/m^3	Environment Density (constant)
c	m/s	Sound Speed (constant)
v	m/s	Particle Speed
ω	rad / s	Angular Speed
ξ	m	Particle Movement
Z	N·s/m^3	Acoustic Impedance
a	m/s^2	Particle Acceleration
I	W/m^2	Sound Intensity
E	W·s/m^3	Sound Energy Density
P$_{ac}$	Watt	Acoustic Power
A	m^2	Surface

summary description takes into consideration this loss which occurs on the transmission distance *d*. The second level calculates the specific loss of one location caused by reflexions and refractions of upper and lower surfaces, i.e. sea surface and bottom and also, the sound speed variations due to depth differences. The result is a better prediction model of a specific transmitter. The third level addresses the apparently random power shifts of the signal received, by considering an average during a period of time. These changes are due to slow variations of the propagation environment, e.g. tidal waves.

All these phenomena are relevant for determining the transmission power needs in order to accomplish an efficient and successful underwater communication. We can also think at a separate model which could address much faster changes of the instantaneous signal power at any given time, but at a far smaller scale. The Signal Noise Ratio for different transmission distances as a frequency function can be viewed in Figure 12.8. The sound absorption limits the bandwidth which can be used for transmission and becomes dependent on the distance:

By evaluating the entity *A(d,f) N(f)* as a function of ideal propagation of the attenuation *A(d,f)* and as a consequence of tipical spectral power of the background noise *N(f)*, which drops 18dB per decade, we find the combined

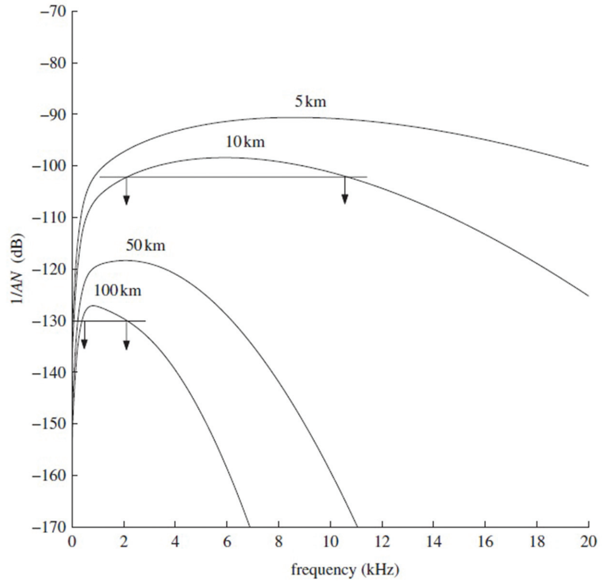


Figure 12.8 Signal-Noise Ratio (SNR).

effect of attenuation and noise in underwater acoustics. This characteristic describes the observation of SNR around the frequency bandwidth *f*. This shows that high frequencies suffer fast attenuation on long distances, which forces most modems to operate on a narrow bandwidth few kHz at most, by suggesting the optimal frequency for a specific transmission [26]. It also shows that the available bandwidth and implicitly the effective transmission rate reduces with higher distances; therefore, the development of any big network should start by determining its specific frequency and reserving a bandwidth around it [27].

12.2.3 Maintenance

Ocean can be a very harsh environment and underwater sensors are prone to failures because of fouling and corrosion. The sensor's construction method could include one miniaturized copper-alloy anode for anti-corrosion, as well as one miniaturized aluminum-alloy anode which could fight fouling. Modern anti-fouling systems already installed on rigs use microprocessor controlled anodes and the current flowing to each anti-fouling and anti-corrosion anode is quite low and the technology could be adapted by miniaturization of the existing anodes. Although we are considering the environmental impact of deploying such a high number of underwater devices, our primary concerns are the feasibility and the durability of the network and how we can address these factors in order to be able to expand our network through time and its enlargement to be backwards compatible to already deployed nodes. Besides the communication protocols being backwards compatible, underwater Safe-Net nodes must possess self-configuration capabilities, i.e. must be able to coordinate their operation, location or movement and data communication handshake protocols by themselves. So, we state the obvious, that this can only be possible if the Safe-Net nodes are resistant enough in the salt, corrosive water of the sea.

12.2.4 Law and Finance

At the end of 2010, the European Commission issued a statement concerning the safety regulations for offshore oil and gas drilling operations, with the declared purpose of developing new laws for the European Union concerning oil rigs. The primary objective of these measures will be the enforcement in this domain of the highest safety standards in the world until present time in order to prevent ecological disasters like the one in the Gulf of Mexico.

Moreover, during March – May 2011, following a public consultation session regarding the European Union legal frame for current practices of marine exploration and production safety standards, the community experts have drawn the line saying that although generally speaking the activities meet high standards of safety, these vary from one company to another, because of the different laws which apply in each country. Therefore, the next legislative proposal should enforce a common ground for all E.U. members concerning the laws for prevention, reaction times and measures in case of emergencies, as well as the *financial liability*.

According to the top 10 list of companies by largest revenues in the fiscal year 2010–2011, 7 are oil and gas industry companies, which summed up \$2.54 billion USD revenues out of a total \$3.43 billion USD. This means more than 74% of the global revenues [28]; therefore, the cost of deploying such Safe-Nets around drilling operations is rather small and the benefits would be huge. Laws could be issued by governments in order to enforce the obligation to oil and gas companies working at sea to use this sensor networks every time a new site is being surveyed or a new jacket is installed. This could also apply to existing oil rigs, jack-ups which move between different places or even for subsea production sites. The ability to have small devices physically distributed near offshore oil-fields' operations brings new opportunities for emergency-cases interoperability up to the higher level of disaster management systems point of view [29].

Ocean Sampling Networks have been experimented in the Monterey Bay area, where networks of sensors and AUVs, such as the Odyssey-class AUVs, performed synoptic, cooperative adaptive sampling of the 3D coastal ocean environment. Seaweb is an example of a large underwater sensor network developed for military purposes of detection and monitoring submarines [30]. Another example is the consortium formed by Massachusetts Institute of Technology (MIT) and Australia's Commonwealth Scientific and Industrial Research Organization which has collected data with fixed and mobile sensors mounted on autonomous underwater vehicles. The network was only temporary and lasted only for a few days around the coasts of Australia [31].

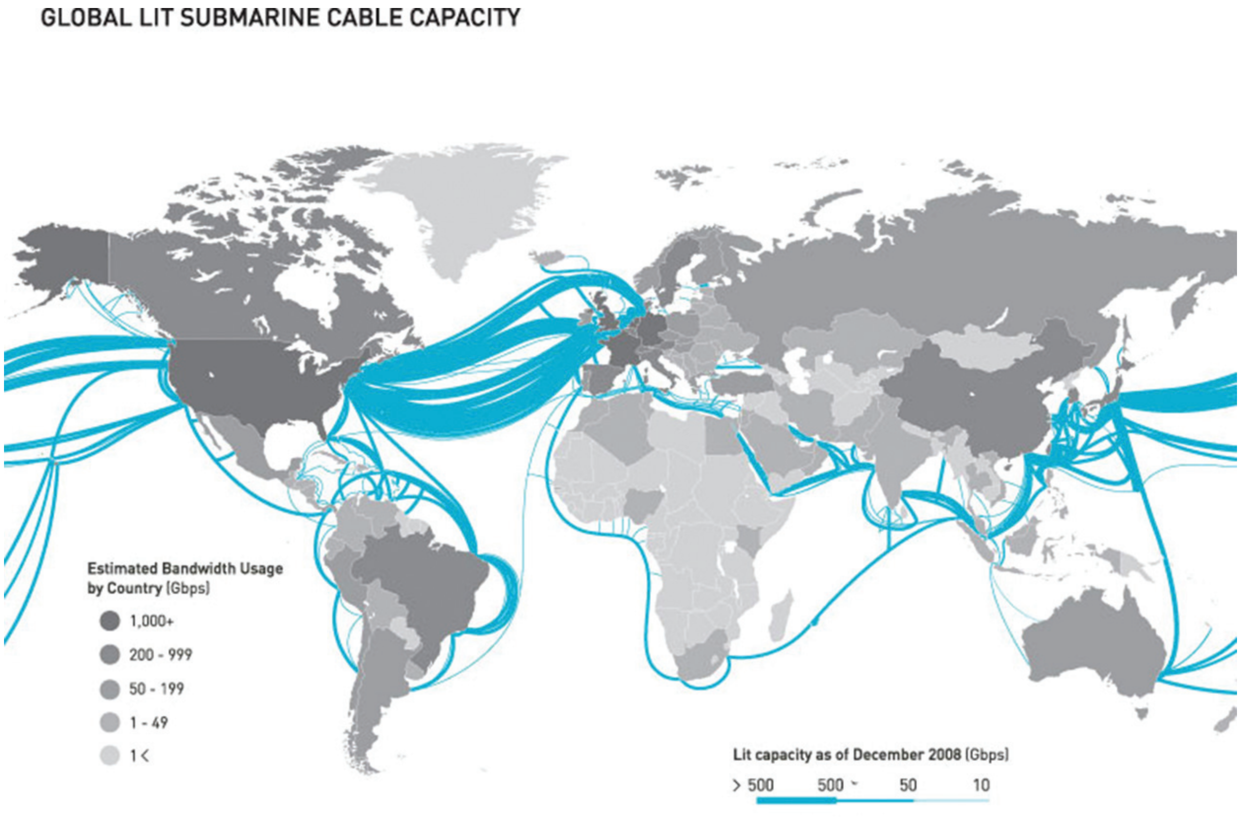
Ocean Observatories Initiative represents one of the largest ongoing underwater cabled networks, which has eliminated both the acoustic communication and power supply problems right from the start, by using already existing underwater cables or new installs. The investment on Neptune project was huge, approximately \$153 billion dollars [32], but the idea seems quite bright if we look at the most important underwater cables, which are already running data under the oceans (Figure 12.9, with courtesy of TeleGeography.com). In 1956, North America was connected to Europe by an undersea cable called TAT-1. It was the world's first submarine telephone system, although telegraph cables had crossed for the ocean for a century. Trans-Atlantic cable capacity soared over the next 50 years, reaching a huge amount of data flowing back and forth the continents, nearly 10 Tbps in 2008.

12.2.5 Possible Applications

- Seismic monitoring. Frequent seismic monitoring is of importance in oil extraction; studies of variation in the reservoir over time are called 4-D seismic and are useful for judging field performance and motivating intervention;
- Disaster prevention and environmental monitoring. Sensor networks for seismic activity mentioned before could also be used for tsunami warnings to coastal areas. While there is always a potential for sudden devastation (see Japan 2011), warning systems can be quite effective. There is also the possibility of pollution monitoring: chemical, biological and so on and so forth;
- Weather forecast improvement: monitoring of ocean currents and winds can improve ocean weather forecasts, detecting climate change and also understanding and predicting the effect of human activities on marine ecosystems;
- Assisted navigation: sensors can be used to locate dangerous rocks in shallow waters. The buoys can also signal the presence of submerged wrecks or potential dangerous areas for navigation;
- Surveillance used for coast-line or border-lines, detecting the presence of ships in country marine belt. Fixed underwater sensors can monitor areas for surveillance, reconnaissance or even intrusion detection systems.

12.3 Mathematical Model

We introduce the class of systems which was considered when conducting the research for the PhD thesis, as well as definitions on configurations of sensors and remote actuators. This class of distributed parameter systems which describes important concepts for parameter identification and optimal experiment design has been adapted from the theoretical and practical research "*Optimal Sensing and Actuation Policies for Networked Mobile Agents in a Class of Cyber-Physical Systems*" [33]. The study presents models for



©2009 TeleGeography

Figure 12.9 Most important underwater data & voice cables (2008).

aerial drones in the U.S.A., which could take high-resolution pictures of the agricultural terrain and the algorithm was pointed to data correlation between meteorological stations on the ground by matching the pictures with the low-resolution ones taken from satellites. The purpose was to introduce a new methodology to transform low-resolution remote sensing date about soil moisture to higher resolution information that contains better knowledge for use in hydrologic studies or water management decision making. The goal of the study was aiming to obtain a high-resolution data set with the help of a combination of ground measurements from instrumentation stations and low-altitude remote sensing, typically images obtained from a UAV. The study introduces optimal trajectories and launching points of UAV remote sensors in order to solve the problem of maximum terrain coverage using least hardware means, also expensive in their case.

We have taken further this study by matching the agricultural terrain with our underwater environment and making an analogy between the fixed instrumentation systems on ground, the meteorological stations and all the fixed offshore structures already put in place through-out the sea. The mobile drones are represented by remotely operated vehicles or by autonomous underwater vehicles which can have data collection sensors on-board and can be used as mobile network nodes. The optimisation of the best distribution pattern of the nodes in the underwater environment can be extrapolated only by neglecting the environment constants, which weren't taken into account by the study [33]. This issue is further to be investigated.

12.3.1 System Definition

The class of distributed parameter systems considered can be described by the state Equation [34]:

$$\begin{cases} \dot{y}\left(t\right) = Ay\left(t\right) + Bu\left(t\right) \\ y\left(0\right) = y_0 \end{cases} , \; 0 < t < T, \tag{12.5}$$

where $Y = L^2(\Omega)$ is the state space and Ω is a bounded and open subset of $\mathbb{R}^n$ with a sufficiently regular boundary $\Gamma = \partial\Omega$. The domain Ω is the geometrical support of the considered system (12.5). A is a linear operator describing the dynamics of the as the set of linear maps from U to Y is the input operator; $u \in \mathcal{L}^2\left(0, T, U\right)$ is the space of integrable functions $f :]0, T[\mapsto U$ such that the function $t \rightarrow \|f\left(t\right)\|^p$ is integrable on $]0, T[$ and U is a Hilbert control space. In addition, the considered system has the following output equation:

$$z(t) = Cy(t), \tag{12.6}$$

Where $C \in \mathcal{L}\left(L^2(\Omega), Z\right)$ and Z is a Hilbert observation space. We can adapt the definitions of actuators, sensors, controllability and observability to system classes that are formulated in the state Equation form (12.5).

The tradition approach of the analysis in distributed parameter systems is fairly abstract in its purely mathematical form. Therefore, all the characteristics of the system related to its spatial variables and geometrical aspects of the inputs and outputs of the system are considered. To introduce a more practical approach from an engineering point of view, the study [33] introduces the concepts of actuators and sensors in the distributed parameter systems point of view. With these concepts at hand, we can describe more practically the relationship between a system and its environment, in our case sea/ocean water. The study can be extended beyond the operators *A*, *B* and *C*, with the consideration of the spatial distribution, location and number of sensors and actuators.

The sensors' measurements are, in fact, the observations on the system, having a passive role. On the other hand, actuators provide a forcing input on the system. Sensors and actuators can be of different natures: zone or point-wise or domain distributed, internal or boundary, stationary or mobile. An additional important notion is the concept of region of a domain. It is generally defined as a subdomain of Ω. Instead of considering a problem on the totality of Ω, the focus can be concentrated only on a subregion $\omega \varepsilon\ \Omega$, while the results can still be extended to $\omega = \Omega$. Such consideration allows the generalization of different definition and methodologies developed in previous works on distributed parameter systems analysis and control.

12.3.2 Actuator Definition

Let Ω be an open and bounded subset of $\mathbb{R}^n$ with a sufficiently smooth boundary $\Gamma = \partial\Omega$ [35]. An actuator is a couple *(D, g)* where *D* represents the geometrical support of the actuator, $D = supp\,(g) \subset \Omega$ and *g* is its spatial distribution.

An actuator *(D, g)* is said to be:

- A zone actuator if *D* is a non-empty sub-region of Ω;

- A point-wise actuator if *D* is reduced to a point $b \in \Omega$. In this case, we have g=∂_b where ∂_b is the Dirac function concentrated at b. The actuator is denoted *(b,*∂_b*)*.

An actuator, zone or point-wise, is said to be a boundary actuator if its support D⊂Γ. An illustration of the actuators supports is given in Figure 12.10:

In the previous definition, we assume that $g \in L^2\left(\mathrm{D}\right)$. For a collection of *p* actuators $(D_i, g_i)_{1 \le i \le p}$, we have $U = \mathbb{R}^p,\ B : \mathbb{R}^p \to L^2\left(\Omega\right)$ and:

$$u\left(t\right) \to Bu\left(t\right) = \sum_{i=1}^{p} g_i u_i\left(t\right), \tag{12.7}$$

$u = (u_1, u_2, \ldots, u_p)^T \in L^2\left(0, \mathrm{T}, \mathbb{R}^p\right)$ and $g_i \in L^2\left(D_i\right)$ with $D_i = supp\left(g_i\right) \subset \Omega$ for $i = 1, \ldots, p$ and $D_i \cap D_j = \emptyset$ for *i* ≠ *j*. So, we have the following:

$$B \cdot y = \left(g_1, y, g_2, y, \ldots, g_p, y\right)^T, \quad z \in L^2\left(\Omega\right), \tag{12.8}$$

where $M^{\ T}$ is the transpose matrix of *M* and $<\cdot,\cdot>=<\cdot,\cdot>_Y$ is the inner product in *Y* and for $v \in Y$, if *supp(v)=D*, we have:

$$\langle v, \cdot \rangle = \langle v, \cdot \rangle_{L^2(\mathrm{D})}. \tag{12.9}$$

When *D* does not depend on time, the actuator *(D,g)* is said to be fixed or stationary. Otherwise, it is a moving or mobile actuator denoted by *(*D_t*,*g_t*)*, where *D(t)* and *g(t)* are, respectively, the geometrical support and the spatial distribution of the actuator at time *t*, as in Figure 12.11:

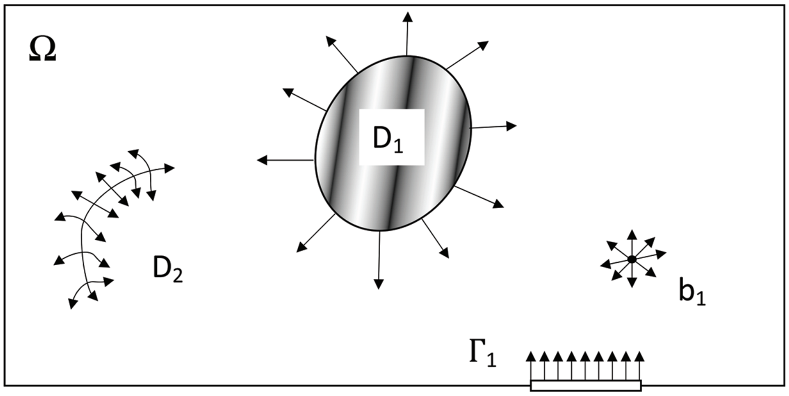


Figure 12.10 Graphical representation of actuators' supports.

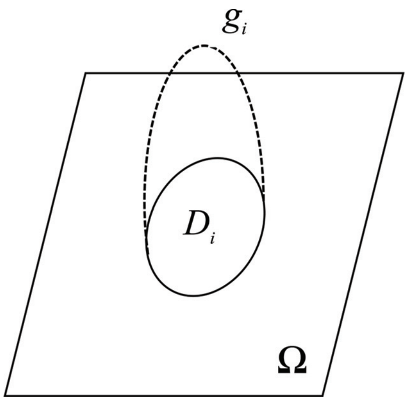


Figure 12.11 Illustration of the geometrical support and spatial distribution of an actuator.

12.3.3 Sensor Definition

A definition of sensors in the distributed parameters systems point of view is provided by [35]: a sensor is a couple *(D,h)* where *D* is the support of the sensor, $D = supp\,(h) \subset \Omega$ and *h* its spatial distribution.

A graphical representation of the sensors supports is given in Figure 12.12:

It is usually assumed that $h \in L^2\,(\mathrm{D})$. Similarly, we can define zone or point-wise, internal or boundary, fixed or moving sensors. If the output of the system is given by means of *q* zone sensors $(D_i, h_i)_{1\leq i\leq q}$ with $h_i \in L^2\,(\mathrm{D}_i)$, $D_i = supp\,(h_i) \subset \Omega$ for $i = 1, \ldots, q$ and $D_i \cap D_j = \phi$ if *i* ≠*j*, then in the

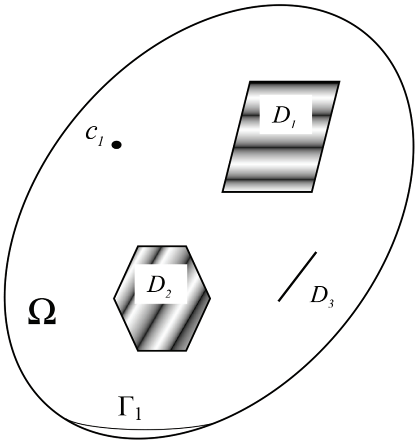


Figure 12.12 Graphical representation of the sensor supports.

zone case, the distributed parameter system's output operator *C* is defined by $C : L^2(\Omega) \rightarrow \mathbb{R}^p$:

$$y \rightarrow Cy = (h_1, y, h_2, y, \ldots, h_p, y)^T . \tag{12.10}$$

And the output is given by:

$$z(t) = \begin{bmatrix} h_1, y_{L^2(\mathrm{D}_1)} \\ \vdots \\ h_q, y_{L^2(\mathrm{D}_q)} \end{bmatrix} . \tag{12.11}$$

A sensor *(D,h)* is a zone sensor if *D* is a non-empty sub-region of Ω. The sensor *(D,h)* is a point-wise sensor if *D* is limited to a point $c \in \Omega$ and in this case $h{=}\partial_c$ is the Dirac function concentrated in *c*. The sensor is denoted as (c,∂_c). If $D \subset \Gamma = \partial\Omega$, the sensor *(D,h)* is called a boundary sensor. If *D* is not dependent on time, the sensor *(D,h)* is said to be fixed or stationary, otherwise it is said to be mobile and is denoted as (D_t,h_t). In the case of *q* point-wise fixed sensors located in $(c_i)_{1 \leq i = \leq q}$, the output function is a *q*-vector given by the relationship:

$$z(t) = \begin{bmatrix} y(t, c_1) \\ \vdots \\ y(t, c_q) \end{bmatrix} . \tag{12.12}$$

Where c_i is the position of the *i*-th sensor and $y(t,c_i)$ is the state of the system in c_i at a given time *t*. [33] based on [36] devines also the notions of observability and local controllability in the sense of distributed parameters systems. [33] also shows that due to the nature of the problem of parameter identification, the abstract operator-theoretic formalism used above to define the dynamics of a distributed parameter system is not convenient. A formalism based on *n* partial differential equations is used instead. According to this setup, the sensor location and clustering phenomenon problem is ilustrated in the Fisher Information Matrix (FIM) [37], which is a well-known performance measure tool when looking for best measurements and is widely used in optimum experimental design theory for lumped systems [38]. Its inverse consitutes an approximation of the covariance matrix for the estimate of Θ. However, there is a serious issue in the FIM framework of optimal measurements for parameter estimation of distributed parameters system, which is the dependence of the solution on the initial guess on parameters [39]. The dependence of the optimal location on Θ is very problematic; however, some *robust design* techniques have been developed in order to minimize or elude the influence and we propose similar methodologies.

By analogy with the study [33], we can try to optimize this solution for underwater points of interest. But in our case, of course, the problems are much more complex because of the physical and chemical properties of the environment.

We can consider two communication architectures for underwater Safe-Nets. One is a two-dimensional architecture, where sensors are anchored to the bottom of the ocean, and the other is a three-dimensional architecture, where sensors float at different ocean depths covering the entire monitored volume region. While the former is designed for networks whose main objective is to monitor the ocean bottom, the latter is more suitable to detect and observe phenomena in the three-dimensional space that cannot be adequately observed by means of ocean bottom sensor nodes. The mathematical model above refers only to the two-dimensional architecture case and we are looking into further researches for the three-dimensional optimization, especially when talking about the sensor-clustering phenomena.

12.4 ROV

A remotely operated vehicle (ROV) is a non-autonomous underwater robot. They are commonly used in deep-water industries such as offshore hydrocarbon extraction. A ROV may sometimes be called a remotely operated underwater vehicle to distinguish it from remote control vehicles operating on land or in the air. ROVs are unoccupied, highly manoeuvrable and operated by a person aboard a vessel by means of commands sent through a tether.

They are linked to the ship by this tether (sometimes referred to as an umbilical cable), which is a group of cables that carry electrical power, video and data signals back and forth between the operator and the vehicle. The ROVs are used in offshore oilfield production sites, underwater pipelines inspection, welding operations, subsea BOP (Blow-Out Preventer) manipulation as well as other tasks:

- Seabed Mining – deposits of interest: gas hydrates, manganese nodules, metals and diamonds;
- Aggregates Industry – used to monitor the action and effectiveness of suction pipes during extraction;
- Cable and Node placements – 4D or time lapse Seismic investigation of crowded offshore oilfields;

- Jack-up & Semi-Submersible surveys – preparation and arrival of a Jack-up or Semi-Submersible drilling rig;
- Drilling & Wellhead support – monitoring drilling operations, installation/removal of template & Blow-Out Preventers (BOP), open-hole drilling (Bubble Watch), regular inspections on BOP, debris removal, IRM and in-field maintenance support (Well servicing);
- Decommissioning of Platforms / Subsea Structures – Dismantle structures safely and environment friendly;
- Geotechnical Investigation – Pipeline route surveys, Pipeline Lay – Startup, Touchdown monitoring, Pipeline Pull-ins, Pipeline crossings, Pipeline Lay-downs, Pipeline Metrology, Pipeline Connections, Post-lay Survey, Regular Inspections;
- Submarine Cables – Route Surveys, Cable Lay, Touchdown monitoring, Cable Post-Lay, Cable Burial;
- Ocean Research – Seabed sampling and surveys;
- Nuclear Industry – Inspections, Intervention and Decommissioning of Nuclear Power Plants;
- Commercial Salvage – Insurance investigation and assessment surveys, Salvage of Sunken Vessels, Cargoes, Equipment and Hazardous Cargo Recovery;
- Vessel and Port Inspections – Investigations, Monitoring of Ports and homeland security.

We are going to use PerrySlingsby Triton XLS and XLR models of the remote operated vehicles (ROV), which are currently available in the Black Sea area. While having the bigger goal in mind - deploying such networks on a large scale - we can only think now for a small test bed and before any physical implementation we are creating simulation scenarios on the VMAX ROV Simulator. Simulation helps preventing any damages to the ROV itself or any of the subsea structures we encounter. This also prevents any real-life impossible design-situations to occur, e.g.: the ROV's robotic arms have very good dexterity and their movement is described by many degrees of freedom - however, sometimes we find out the limits of motion and in some given situations, deploying objects in some positions may prove difficult or even impossible. We address these hypothetical situations and try to find the best solutions for securely deploying the sensors by anchors to the sea floor or by tethering to any metallic or concrete structures: jackets, jack-up legs, autonomous buoys, subsea well production heads, offshore wind farm production sites, so on and so forth.

In the Black Sea area, operating in Romania’s territorial sea coast line, we identified 4 working-class ROVs, out of which 2 are manufactured by PerrySlingsby U.K.: 1 Triton XLX and 1 Triton XLR - first prototype of its kind, which led to our models used in simulation.

12.4.1 ROV Manipulator Systems

Schilling Robotics’ TITAN 4 manipulator with 7 degrees of freedom (Figure 12.13) is the industry’s premier system that offers the optimum combination of dexterity and strength. Hundreds of TITAN manipulators are in use worldwide every day, and are the predominant manipulator of choice for work-class ROV systems. Constructed from titanium, the TITAN 4 is uniquely capable of withstanding the industry’s harsh environment and repetitive needs.

The movement of the 7-function Master Arm Control (Figure 12.14) is transmitted through the fibre optics inside the tether and the underwater media converters situated on the ROV pass the information to the Titan 4 Manipulator after it is checked for send/receive errors. The exact movement of the joints of the 7-function above the sea level represent the movement of the Titan-4

Figure 12.13 Titan 4 Manipulator 7-F.

Figure 12.14 Master Arm Control.

underwater. This provides the dexterity and degrees of freedom needed to execute most difficult tasks (Figure 12.15):

Schilling's RigMaster is a five-function, rate-controlled, heavy-lift grabber arm that can be mounted on a wide range of ROVs (Figure 12.16). The grabber arm can be used to grasp and lift heavy objects or to anchor the ROV by clamping the gripper around a structural member at the work site.

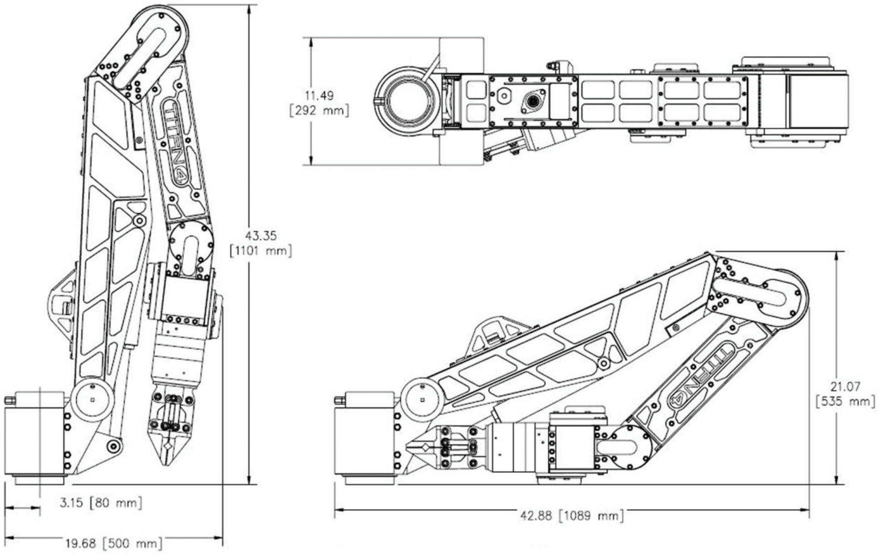


Figure 12.15 Titan 4 – Stow dimensions.

Figure 12.16 RigMaster 5-F.

Constructed primarily of aluminium and titanium, the RigMaster delivers the power, performance, and reliability required for such demanding work. A typical work-class ROV utilizes a combination of the five-function RigMaster and seven-function TITAN 4.

With these two manipulator systems, any type of sensor can be deployed or fixed on the ocean bottom. In order for a better understanding of the process and likely problems which can occur during the installation, we are going to use the VMAX Tech. – PerrySlingsby ROV Simulator for which we are going to develop a modelling and simulation scenario concerning the deployment of

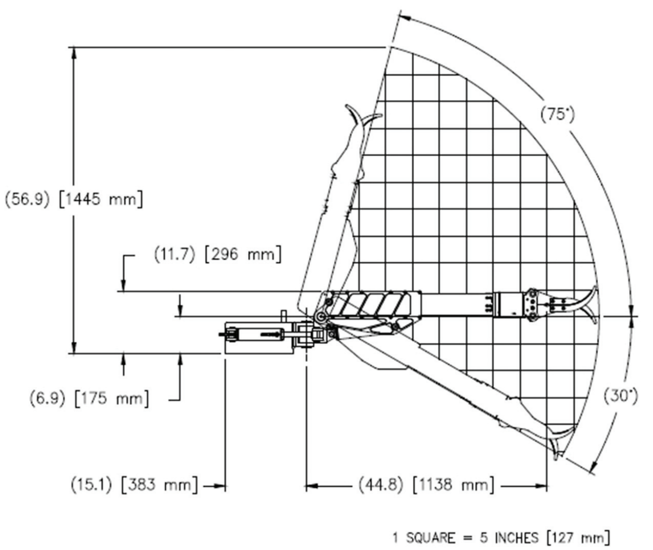


Figure 12.17 RigMaster range of motion – Side view.

underwater sensors Safe-Net surrounding areas of offshore oil and gas drilling operations.

12.4.2 Types of Offshore Constructions

Offshore constructions represent the installation of structures and facilities in a marine environment, usually for the production and transmission of electricity, oil, gas or other resources. We have taken into consideration most usual encountered offshore types of structures and facilities, focusing on the shapes which are found underwater:

- Fixed platforms;
- Jack-up oil and gas drilling and/or production rigs;
- Jackets with top sides;
- Spars or floating platforms;
- Semi-submersibles;
- Drilling ships;
- Floating tension legs;
- Floating production storage and offloading (FPSO);
- Subsea well production heads;
- Offshore wind farm production sites.

We have created a simple scenario in which we use a PerrySlingsby Triton XLS ROV connected to a TMS (Tether Management System) and where we can use the physics of the robotic arms in order to understand which movements are going to be needed in order to implant sensors of different sizes into the ocean floor, as well as nearby the types of subsea structures mentioned above. We try to create handling tools for the Schilling Robotics 7-F arm in order to easily deploy and fix or common framework device model and also try to find best spots for all the offshore types of structures we encountered in our offshore experience inquiry [40].

12.5 ROV Simulator

The VMAX Simulator is software and hardware package intended to be used by engineers to help in the design process of procedures, equipment and methodologies, having a “physics based simulation” for the offshore environment. The simulator is capable of creating scenarios that are highly detailed and focused on one area of operation or broad in scope to allow an inspection of an entire subsea field. For creating a scenario, there are two skill sets needed: 3D Studio Max modelling and ".lua" script programming skills.

In order to safely deploy our Safe-Nets' sensor balls into the water and fix them to jack-up rigs metallic structures or to any other offshore constructions, we first try to develop models of those structures and include them into a standard fly-alone ROV simulation scenario. This is a two-step process as any object's model has to be created in 3D Studio Max software and afterwards it can be programmatically be inserted into the simulation scenario. The simulation scenarios are initialized by a series of Lua scripts, which is very similar to C++ programming language and The VMAX Scenario Creation is *open source*. The scripts are plain text files that can be edited using many programs, including Microsoft Windows Notepad. The file names end with .lua extension and are recommended to be opened with jEdit editor. This is also an open-source editor which requires the installation of Java Runtime Environment (JRE).

We have altered the simulation scenarios as it can be seen in Figure 12.18 and Figure 12.19 in order to obtain a better model of the Black Sea floor through-out Romania's coast line, which usually contains more sand because of the Danube sediments coming from The Danube Delta. Geologists working on-board the Romanian jack-ups considered the sea-floor in the VMAX ROV Simulator very much alike with the one in the geological and oil-petroleum interest zones up to 150-160 miles out in the sea. Throughout these zones the water depth doesn't exceed 80-90m, which is the limit at which drilling jack-up rigs can operate (legs have 118m in length).

The simulator which is open-source was the starting base for a scenario where we translated the needs of the ROV in terms of sensor handling, tether positioning and pilot techniques combined with the specifications of the sea-floor where the Safe-Nets will be deployed. The scenarios are initialized by a series of .Lua scripts and the typical hierarchical file layout is presented in Figure 12.20.

The resources are divided into two large classes of information: *Scenarios*-related data and *Assets*. The former contains among others: Bathymetry, Lua, Manipulators, Tooling, TMS (Tether Management System), Vehicles, Components and IP (Internet Protocol communications between assets).

Bathymetry directory contains terrain information about a specific location, where we could alter the sand properties on the sea floor. The terrain stored here may be used across several scenarios. We could add a graphic asset by using the template for the bathymetry part. The collision geometry can be later generated based on the modelled geometry. We remind that the

Figure 12.18 Triton XLS ROV in simulation scenario.

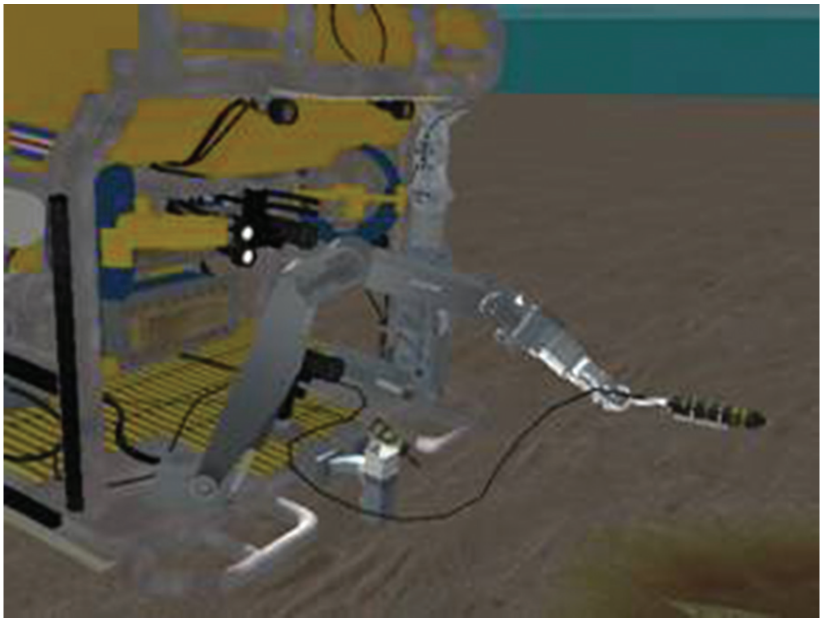


Figure 12.19 Triton XLS schilling robotics 7-Function arm in scenario.
Courtesy of TelegeoGraphy.com

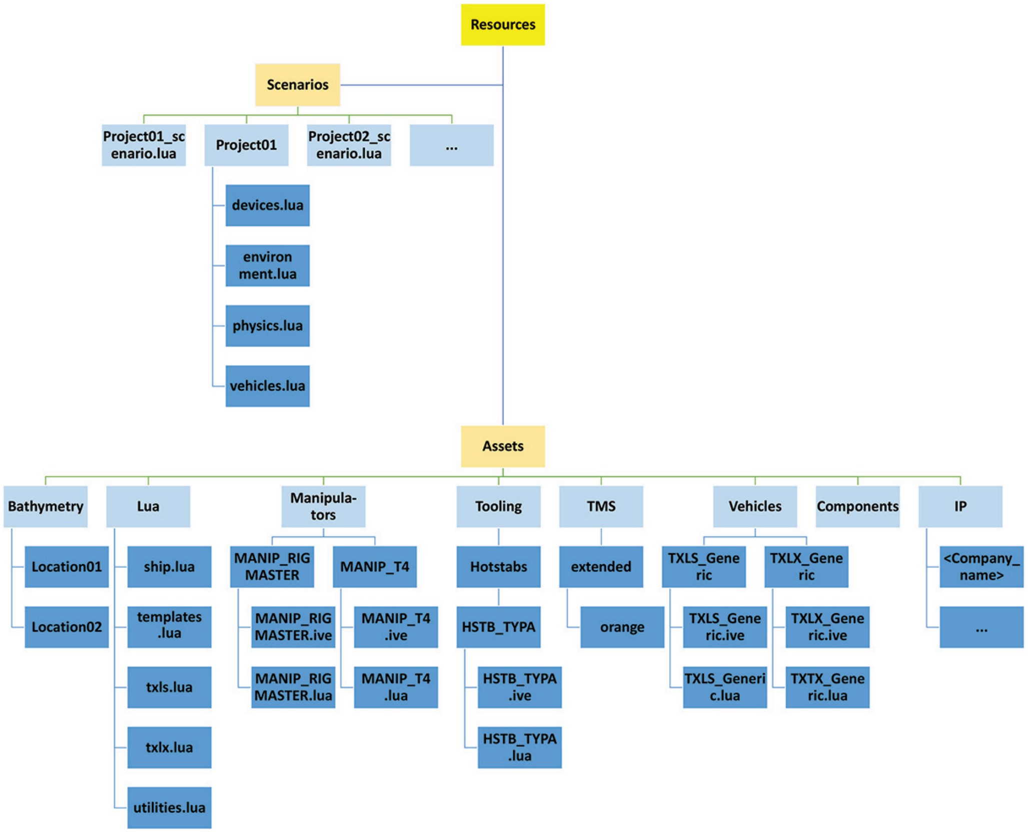


Figure 12.20 Typical hierarchical file layout.

simulator scenario creation software is *open-source* and we present in the following lines some of the parts of the basic scenario provided with the full-up simulator which we modified in order to accommodate our specific needs:

```
graphicAsset {
assetID = "bathymetry",
castShadow = true,
– can be false for very flat terrain
– Our terrain model =
"assets/Bathymetry/TER_500m_v2.0/TERBLKSEA_500m_v1.0.ive",
receiveShadow = true,
scale = { 2, 2, 2 }
– specific to this particular model
}
–We changed the environment table to look like this:
environment = {
assembly = {
– Various items in the environment starting with bathymetry.
parts = {
– add the bathymetry based on a template
createFromTemplate(templates.bathymetry,
{
collisions = {
– The first item in the array is for the collision
– geometry automatically created from the model.
{
– set the area over which the bathymetry spans
size = { 100, 100, 1 },
– must be specified
}
– collision primitives may be appended to this array
},
– set the depth of the bathymetry
position = { 0, 0, REFERENCE_DEPTH - 20 }}),}
constraints = { },
selfCollide = true,},
bathymetryPartName = "bathymetry",
pickFilter = { "bathymetry" },
```

```
currentDirectionTable = { 0 },
currentSpeedTable = { 1 },
depthTable = { 0 }}
```

The bathymetry template uses triangle mesh collision for the terrain. This will provide collisions that are contoured to the bathymetry model

The Manipulators directory contains sub-directories for each arm and each sub-director contains a model file with a .Lua script function used to create the manipulator and add it to the ROV. We are looking forward to creating a new manipulator usable for each case of sensor deployment.

The Tooling directory has either categories of tools or some uncategorized ones, each having a model file name ".ive" or ".flt" and a Lua script file with the code to create that specific tool [41].

Whereas the typical training scenarios include mainly a fly-around and getting used to the ROV commands for the pilot and assistant pilot, we have used the auxiliary commands in order to simulate the planting of the Safe-Net around a jacket or a buoy for example. As far as the training scenario is concerned, we covered the basics for a pilot to get around a jacket safely, carrying some sort of object in the Titan4 manipulator robotic arm, without dropping it, or without having the ROV's tether tangling with the jacket metallic structure. The tether contains hundreds of fibre-optic cables covered with a Kevlar reinforcement, but it is recommended that no more than 4 total 3600 spins are made in one direction, clockwise or counter-clockwise, even having this strengthened cover, in order to avoid any loss of communication between the control console and the ROV itself. Any interaction between the tether and the metallic structure could represent a potential threat to the ROV's integrity.

12.6 Common Modular Framework

An overview of the challenges and application possibilities of deploying underwater sensor networks nearby oil rigs drilling operations areas and offshore construction sites surroundings led to the conclusion that a standard device is needed in order to deploy multi-purpose underwater sensor networks. We detected the need for a standard, common, easy-to-use device framework for multi-purpose underwater sensors in marine operations, as we were preparing the devices for future use. This framework should be used for multiple different sensors and we consider the modular approach to be best suited for future use, providing the much-needed versatility.

We considered the buoyancy capabilities needed for a stand-alone device launched on the sea surface and we started with an almost spherical-shaped model Figure 12.21. If tethering should be needed, a small O-ring cap on one of the sphere's poles can be mounted:

The device will be able to accommodate a variety of sensors, adapted within the inside "drawers", its layers being highly modular. In this manner, with the same network node, we will be able to empower a lot of types of applications and this is an essential step in justifying the costs of development. We believe this characteristic is critical for improving the financial desirability of any future Safe-Nets offshore project.

Our simulation scenario is still scarce in modelled objects as the process of creating them quite realistic is taking a long time. However many simulation scenario variables we may alter, after finding out real types of situations which occur on offshore structures, we learned that simulating the deployment and deciding spots of anchoring for our sensors can only help, but not solve real-life deployment, as parameters decided beforehand on shore can change dramatically offshore.

However, we believe that our 3D models for underwater multi-purpose sensors still stand as a good idea for our Safe-Nets real-life development and implementation. Tethered or untethered, the upper hemisphere can include a power adapter which can be used also as batteries compartment if the sensor is wireless. The sensors have enough drawers for electronic modules and Type 03 is designed with built-in cable management system. Also, Type 03 is designed with a membrane for a sensitive pollution sensor. We have chosen a very simple closing mechanism for starters, using clamps on both sides, which can

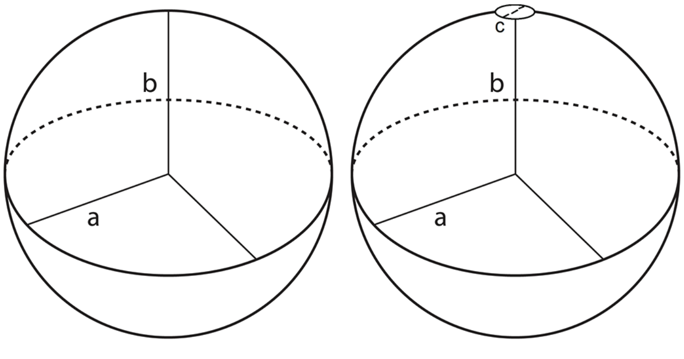


Figure 12.21 Spherical-shaped model designed for common framework; a >= b; c is Tether/Cable entry point diameter.

ensure the sealing of the device. The upper and lower hemispheres close on top of an O-ring seal which can be lubricated additionally with water repellent grease. Also, we have designed a unidirectional valve which can be used for a vacuum pump to clear out the air inside. The vacuum strengthens the seal against water pressure. In Figure 12.22, we present a few prototypes which we tried to model and simulate:

Within the same common modular framework, we have thought at a multi-deployment method for 3 or more sensors at the same time. Actually, the following ideas were issued because of the repeated fail trials with an ROV to grab and hold a Safe-Net sensor long enough in order to place it in a hook coming from an autonomous buoy above the sea surface, affected by wave length and height. Because of the real difficulties encountered, especially when inserting higher waves into the scenario, we have thought of a way to get the job done more quickly (Figure 12.23):

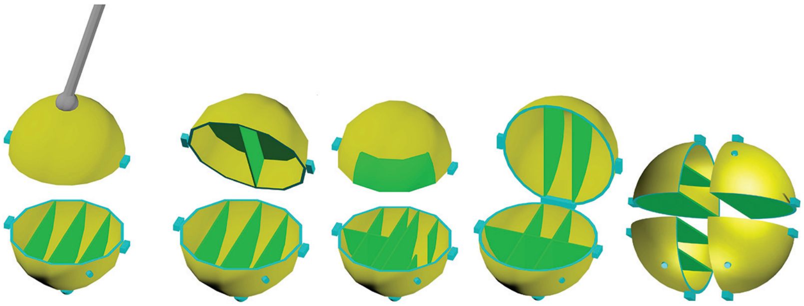


Figure 12.22 Underwater multi-purpose devices prototypes 01 – 05.

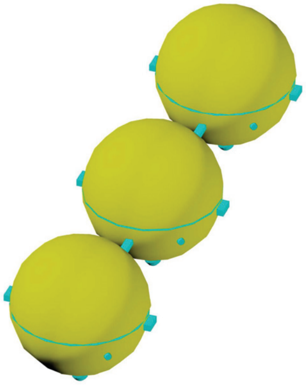


Figure 12.23 Grouping method for multiple simultaneous sensor deployment.

Moreover, the spherical model framework of the sensor, the basic node of the Safe-Net, will prove to be very difficult to handle using the simple manipulator, as it tends to slip, and the objective is to carry it without dropping. Therefore, we have designed a "cup-holder" shape for grabbing more easily the sphere and if it contains a cable connection, it should not be tampered by the grabber, as it can be seen in Figure 12.24:

12.7 Conclusions

Most of the state-of-the-art solutions regarding underwater sensor networks rely on specific task-oriented sensors, which are developed and launched with different means and no standardization. The studies we found usually use power from batteries and all sorts of resilient algorithms in order to minimize battery draining and use sleep-awake states of the nodes, which finally are recovered from water in order to retrieve data collections. Our approach is trying to regulate the ways of deploying and fixing the sensors towards offshore structures and moreover to offer solutions to more than one application task. This may seem as a general approach, but this is needed in order to avoid launching different technology nodes which afterwards will not be able to communicate with each other. Development of a virtual environment-based training system for ROV pilots could be the starting point for deploying underwater sensor networks worldwide, as these are the people who will actually be in the position to implement it.

This chapter investigates the main challenges for the development of an efficient common framework for multi-purpose underwater data collection

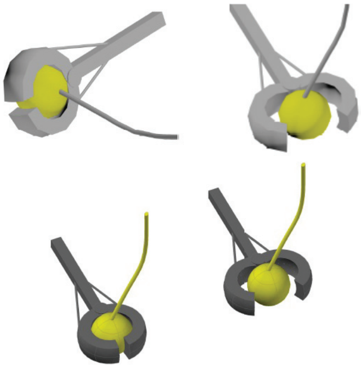


Figure 12.24 Basic sensor device holder designed for simulation.

devices (sensors). Several fundamental key aspects of underwater acoustic communications are also investigated. We want to deploy around existing offshore constructions and this research is still a work in progress. The main challenges for the development of efficient networking solutions posed by deploying sensors in the underwater environment are detailed at all levels. In short, this article has analyzed the necessity of considering the physical fundamentals of an underwater network development in the planetarium ocean, starting from the instrumentation needs surrounding offshore oil drilling sites and early warning systems for disaster prevention worldwide.

We suggest various extension possibilities for applications of these safenets, starting from pollution monitoring around offshore oil drilling sites, early warning systems for disaster prevention (earthquakes, tsunami) or weather forecast improvement, up to military surveillance applications, all in order to overcome the cost of implementation of such underwater networks.

References

[1] K. Eshghi and R. C. Larson, ‘Disasters: lessons from the past 105 years’, Disaster Prevention and Management, Vol. 17, pp.61–82, 2008.

[2] D. Green, ‘Acoustic modems, navigation aids and networks for undersea operations’, IEEE Oceans Conference Proceedings, pp.1–6, Sydney, Australia, May 2010.

[3] J. Heidemann, Y. Li and A. Syed, ‘Underwater Sensor Networking: Research Challenges and Potential Applications’, USC Information Sciences Institute, USC/ISI Technical Report ISI-TR-2005–603, 2005.

[4] T. Melodia, Ian F. Akyildiz and D. Pompili, ‘Challenges for Efficient Communication in Underwater Acoustic Sensor Networks’, ACM Sigbed Review, vol.1, no.2, 2004.

[5] A. Cerpa and et al., ‘Habitat monitoring: Application driver for wireless communications technology’, ACM SIGCOMM Workshop on Data Communications in Latin America and the Caribbean, San Jose, Costa Rica, 2001.

[6] D. Whang, N. Xu and S. Rangwala, ‘Development of an embedded sensing system for structural health monitoring’, International Workshop on Smart Materials and Structures Technology, pp. 68–71, 2004.

[7] D. Steere, A. Baptista and D. McNamee, ‘Research challenges in environmental observation and forecasting systems’, 6th ACM International Conference on Mobile Computing and Networking, Boston, MA, USA, 2000.

[8] L. Dignan, 'Google's Data Centers', [Online] 2011.http://www.zdnet.com/blog/btl/google-makes-waves-and-may-have-solved-the-data-center-conundrum/9937http://www.datacenterknowledge.com/archives/2008/09/06/google-planning-offshore-data-barges/.

[9] A. S. Outlaw, 'Computerization of an Autonomous Mobile Buoy', Florida Institute of Technology, Vol. Master Thesis in Ocean Engineering, Melbourne, FL, 2007.

[10] C. Garcier, et al., 'Autonomous Meteorogical Buoy', Instrumentation Viewpoint, vol. 7, Winter, 2009.

[11] V. Dache, M.C. Caraivan and V. Sgarciu, 'Advanced Building Energy Management Systems - Optimize power consumption', INCOM 2012, pp. 426, Bucharest, 2012.

[12] C. Hong-Jun, et al., 'Challenges: Building Scalable and Distributed Underwater Wireless Sensor Networks (UWSNs) for Aquatic Applications', UCONN CSE Technical Report, UbiNet-TR05–02, 2005.

[13] D. Pompili, T. Melodia and A.F. Ian, 'A Resilient Routing Algorithm for Long-term Applications in Underwater Sensor Networks', Atlanta, 2005.

[14] Aquaret, [Online], 2008. www.aquaret.com

[15] PelamisWaves, [Online], 2012. http://www.pelamiswave.com/pelamis-technology

[16] WaveBob, [Online], 2009. http://www.wavebob.com

[17] Buoy, OE, [Online], 2009. www.oceanenergy.ie

[18] PowerBuoy, [Online], 2008. www.oceanpowertechnologies.com

[19] Oyster, [Online], 2011. www.aquamarinepower.com

[20] WaveDragon, [Online], 2011. www.wavedragon.net

[21] AWS, [Online], 2010. http://www.awsocean.com

[22] F. Mosca, G. Matte and T. Shimura, 'Low-frequency source for very long-range underwater communication', Journal of Acoustical Society of America Express Letters, vol. 133, 10.1121/1.4773199, Melville, NY, U.S.A., 20 December 2012.

[23] D. Pompili and T. Melodia, 'An Architecture for Ocean Bottom UnderWater Acoustic Sensor Networks (UWASN)', Georgia, Atlanta, 2006.

[24] R. Urick, 'Principles of underwater sound', McGraw Hill Publishing, New York, NY, U.S.A., 1983.

[25] S.W. Rienstra and A. Hirschber, 'An Introduction to Acoustics', Eindhoven University of Technology, Eindhoven, The Netherlands, 2013.

[26] J. Wills, W. Ye and J. Heidemann, ‘LowPower Acoustic Modem for Dense Underwater Sensor Networks’, USC Information Sciences Institute, 2008

[27] M. Stojanovic, ‘On the relationship between capacity and distance in an underwater acoustic communication channel’, ACM Mobile Computing Communications, Rev.11, pp.34–43, doi:10.1145/1347364.1347373, 2007.

[28] Wikipedia.org, Wikipedia List of Companies by Revenue, [Online], 2011. http://en.wikipedia.org/wiki/List_of_companies_by_revenue

[29] V. Nicolescu, M. Caraivan, ‘On the Interoperability in Marine Pollution’, IESA’14 7th International Conference on Interoperability for Enterprise Systems and Applications, Albi, France, 2014.

[30] J. Proakis, J. Rice, et al., ‘Shallow water acoustic networks’, IEEE Communications Magazine, pp. 114–119, 2001.

[31] I. Vasilescu, et al., ‘Data collection, storage and retrieval with an underwater sensor network’, 3rd ACM SenSys Conference Proceedings, pp.154–165, San Diego, CA, U.S.A., November 2005.

[32] P. Fairley, ‘Neptune rising’, IEEE Spectrum Magazine #42, pp. 38–45, doi:10.1109/MSPEC.2005.1526903, 2005.

[33] C. Tricaud, ‘Optimal Sensing and Actuation Policies for Networked Mobile Agents in a Class of Cyber-Physical Systems’, Utah State University, Logan, Utah, 2010.

[34] A. El Jai, ‘Distributed systems analysis via sensors and actuators’, Sensors and Actuators A’, vol. 29, pp.1–11, 1991.

[35] A. El Jai and A.J. Pritchard, ‘Sensors and actuators in distributed systems’, International Journal of Control, vol. 46, iss. 4, pp. 1139–1153, 1987.

[36] A. El Jai, et al., ‘Regional controllability of distributed-parameter systems’, International Journal of Control, vol. 62, iss. 6, pp.1351–1356, 1995.

[37] E. Rafajowics, ‘Optimum choice of moving sensor trajectories for distributed parameter system identification’, International Journal of Control, vol. 43. pp.1441–1451, 1986.

[38] N.Z. Sun, ‘Inverse Problems in Groundwater Modeling’, Theory and Applications of Transport in Porous Media, Kluwer Academic Publishers, Dodrecht, The Netherlands, 1994.

[39] M. Patan, ‘Optimal Observation Strategies for Parameter Estimation of Distributed Systems’, University of Zielona Gora Press, Zielona Gora, Poland, 2004.

[40] M. Caraivan, V. Dache and V. Sgarciu, 'Simulation Scenarios for Deploying Underwater Safe-Net Sensor Networks Using Remote Operated Vehicles', 19th International Conference on Control Systems and Computer Science Conference Proceedings, IEEE CSCS'19 BMS# CFP1372U-CDR, ISBN: 978–0-7695–4980-4, Bucharest, Romania, 2013.

[41] B. Manavi, VMAX Technologies Inc. Help File, Houston, 77041–4014 Texas, TX, U.S.A., 2010.