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Design of a sensor network with adaptive sampling

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Abstract: This paper presents the preliminary design of a marine sensor network with high spatial-density of nodes, which uses artificial intelligence techniques to observe episodic events of dynamic natural phenomena in shallow waters. The focus of the research is on how to use intelligent data analysis and reactive behavior to improve the management of network resources, thus increasing the quality of the data collected or reducing the costs of the associated technology.

1 INTRODUCTION

In the emerging research field of marine observation systems composed of sensor networks it is useful to differentiate between deep sea and coastal networks, given the different environmental conditions and scientific interests. Important initiatives involving advanced networks in deep sea scenarios include ARENA (Kasahara et al. [2003]), NEPTUNE (Barnes et al. [2007]), ALOHA/MARS Mooring (Duennebier et al. [2006]) and ESONET (Priede et al. [2003]), while initiatives involving shallow water deployments include LOBO (Johnson et al. [2007]) and the Australian Coral Reef Sensor Network (Bondarenko et al. [2007]). The expansion of this technology is due to the fact that sensor networks facilitate and improve the coordination of sampling at several temporal and spatial scales. That is, sensor networks can be used to observe phenomena ranging from resolutions of minutes to resolutions of years and from resolutions of centimeters to resolutions of kilometers.

The control of sensors' operation generally needs some software, which can be of different degrees of sophistication. Artificial intelligence (AI) techniques have been applied to environmental problems for a long period of time with good results, as for example in environmental planning (Wright et al. [1993]), fish stock prediction (Sazonova et al. [1999]) or wastewater management (Ceccaroni et al. [2004]), just to name a few. The first reliable applications of AI to environmental issues appeared in the 1980's. More recently, AI research has been oriented towards the development of knowledge-based systems (KBSs), which, when applied to environmental issues receive different denominations, such as environmental decision support systems (Cortés et al. [1999]) or environmental KBS. An environmental KBS is a system, applied to an environmental issue, that potentially reduces the time in which decisions are made by the agents involved (e.g., the network nodes) and improves the consistency and quality of those decisions. Advancements in KBS research have the potential of benefiting many environmental fields, as well as very different disciplines. These advancements are in general results in applied optimization, process-control improvements, environmental decision-making and adaptive behavior.

In this paper, sensors capable of integrating highly sophisticated software are considered. In these cases, the software can be referred to as a KBS. Sensor networks can be connected to remote control centers or be autonomous. Data can be gathered in real time or collected at specific

times. If a network is connected to a control center, the sampling parameters of its equipment can be modified at will, to correct misbehavior or to accomplish new objectives. If a network is autonomous, to dynamically adapt to changes in the environment, reactive linear planning can be integrated into the equipment's control software in such a way that sensors:

- receive and possibly process on-line information about the process or phenomenon or parameter being sampled;
- use this information for selecting and revising models of the sampling dynamics;
- apply these models for autonomously planning the control of sampling and for supporting sensors' management by operators.

This adaptive behaviour, detailed in section 2, allows a more intelligent sampling and finally a better management of the network resources, including a reduction of energy consumption and of communication-bandwidth needs.

2 WHY IS ADAPTIVE SAMPLING NEEDED?

In the present study we aim to design an adaptive sensor network for shallow waters, with operational oceanography¹ and environmental monitoring purposes in mind; a network with nodes located a few kilometers from each other and not meant to be used under extreme environmental (especially, pressure) conditions, such as those of deep oceans.

Nowadays, the energy required to acquire data from sensors is used to: cancel noise through filters, amplify and digitize analog signals sensed, process and transport information, as shown by Raghunathan et al. [2006]. Sensors often require high-rate analog-to-digital converters with large power-demands. Power and data-transmission bandwidth are the most limited resources and should be used efficiently, as shown by Akyildiz et al. [2002]. Therefore, ideally a sensor network should guarantee that the sampling happens only if needed, when needed, where needed, and with the adequate level of fidelity. This kind of efficient sampling behavior would reduce the energy used for processing and communication.

Bio-geo-physical phenomena and most of the signals of natural origin have a highly intermittent behavior (e.g., wind gusts, turbulences, algal blooms). An intelligent analysis at network level can reactively plan the sampling through the detection and detailed characterization of episodic events. An example is sun radiation, shown in Figure 1. Cases (a) and (c) correspond to sunny days; these episodes can be easily reproduced by standard mathematical models, therefore a high temporal resolution is not needed. That is, if the interpretation of the signal can be easily inferred from a few data points, sampling can be at low rates. Case (b) corresponds to a cloudy day; it cannot be easily interpreted by current models due to its complexity, and its high variability would benefit from the use of high resolution sampling rates. Low resolution sampling rates should, then, be used in the periodic intervals with no radiation (night time). The general goal is to dedicate more resources to the most significant data intervals and to save resources when data are less relevant.

Another example is a system managing a wide-area sensor network, which could identify sub-regions of particular interest via low-resolution sampling, and then prompt a higher-resolution sampling for the sensors located in those sub-regions.

Finally, adaptive sampling could be used in such a way that sensors in adjacent regions could be reactively alerted in case of need, modifying their future behavior. For example, if a node detects a harmful algal bloom (HAB), it modifies its sampling parameters and sends a notification to neighbor nodes. These nodes use this notification as an additional input parameter for their decision systems, using the information to decide if the data they are measuring indicate the

¹Operational oceanography is the activity of systematic and long-term routine measurements of seas, oceans and atmosphere, and their rapid interpretation and dissemination.

presence of a HAB of the same type. Figure 2 shows part of this behavior, specifically how the network reacts to HAB presence. In the figure, arrows represent data transmission between nodes. In (a) all the nodes are working at low sampling rate. In (b) a HAB appears on a region monitored by two of the nodes. In (c) the affected nodes change to high sampling rate, and alert neighbor nodes and the shore station.

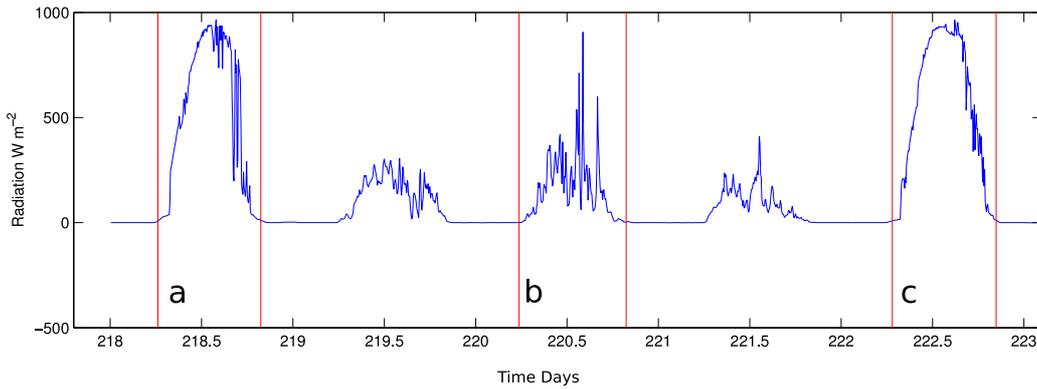


Figure 1: Example of signal (sun radiation), whose observation and post-processing would benefit from intelligent variation of sampling rates

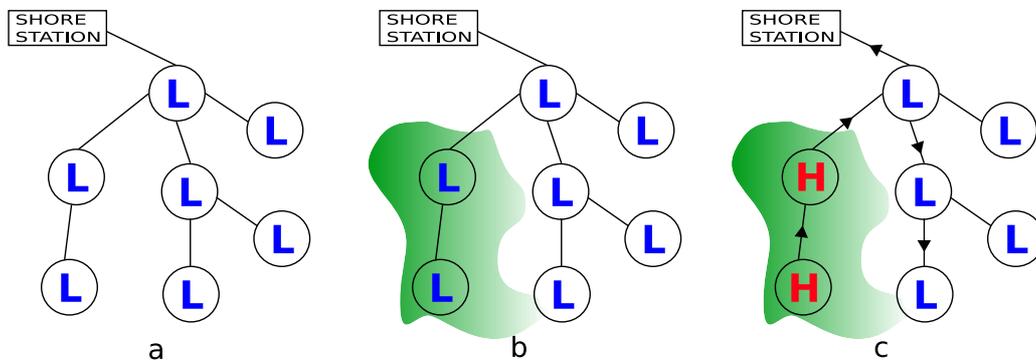


Figure 2: Network’s reactive behavior. ”L” indicates a node working at low sampling rate and ”H” indicates a node working at high sampling rate.

Moreover, if a node has sampling equipment with motion capabilities, such as autonomous vertical profilers² (AVPs), it could be able to identify the points of most interest and sample at high resolution only at those points. In the case of AVPs, the sensors could move up and down the water column looking for depths with particularly interesting data (e.g., thin algal layers), and reduce its speed at these points, simultaneously increasing the sampling rate.

3 TECHNICAL CONSIDERATIONS

Three main technical topics are dealt with in this preliminary design of a marine sensor network:

²A vertical profiler is composed of a sampling module with positive floatability, with a winch and a cable attached to the sea floor. Releasing or winding up the cable, the system can modify its depth.

- network infrastructure;
- adaptive behavior of the network;
- intelligence at the node level.

The first topic taken into account is the **network infrastructure**. The connection among nodes can be fully cabled or acoustic/wireless. Wireless communications could present difficulties due to absorption, that increases with frequency, as shown by Akyildiz et al. [2005] and have in some case limited bandwidth; while the main drawback of cabled networks is the installation cost. Related to the needed bandwidth, when communications are in real time, a good management of the resources and the processing of the gathered data allows to use lower transmission rates. When communications are asynchronous, data can be stored locally at the nodes and sent when bandwidth is available. Even systems that deal with large amounts of data do not need constant streaming, nor constant storage. For example, in the case of high definition cameras, images are captured only when motion is detected. If not, data is discarded, neither stored nor sent.

When dealing with complex environmental problems, with processes that are not easily modeled because our knowledge is still incomplete and uncertain, environmental KBSs can be useful. Regarding the **adaptive behavior of a sensor network**, KBSs, considered as intelligent information systems that allow autonomous decisions and improve the time in which decisions can be made as well as the consistency and the quality of these decisions, represent an interesting approaches to infer spatiotemporal relationships among descriptors measured by sensor nodes. An important feature of KBSs is that they allow the use and management of specialized knowledge, which may include, among others:

- empirical knowledge about organisms and their environment;
- situational knowledge about local environmental conditions and its possible relation with the global environment;
- knowledge about human beliefs, intentions and priorities;
- theoretical knowledge about biological, physical and chemical phenomena.

The proposed research is centered in particular on *rule-based expert systems* (RBESs) and *case based reasoning* (CBR) systems. RBESs are advanced computer programs which emulate, or try to, the human reasoning and problem-solving capabilities, using the same knowledge sources, within a particular discipline. RBESs possess a fact base or ontology, a knowledge-base made of rules, and some inference and search process. The problems addressed through RBESs are very complex and related to specific domains, and they would usually need a human expert (i.e., a large amount of knowledge) to be solved. The central idea of CBRs is that the solution from some past case is reused to solve the current problem. By recalling old solutions given to similar problems and adapting them to fit the new problems, CBR systems can improve their performance, becoming more efficient. Furthermore, they do not have to solve new problems from scratch. The memorization of past problems or episodes is integrated with the problem-solving process, which thus requires the access to past experience to improve the system's performance. Additionally, case-based reasoners, becoming more competent during their functioning over time, can derive better solutions when faced with equally familiar situations because they do not repeat the same mistakes (learning process). If nodes of a sensor network include complex systems, such as vertical profilers, the incorporation of some **intelligence** in the form of reactive behavior (see Figure 3), adopting for instance the approach of CBR systems, can optimize their processing and autonomy.

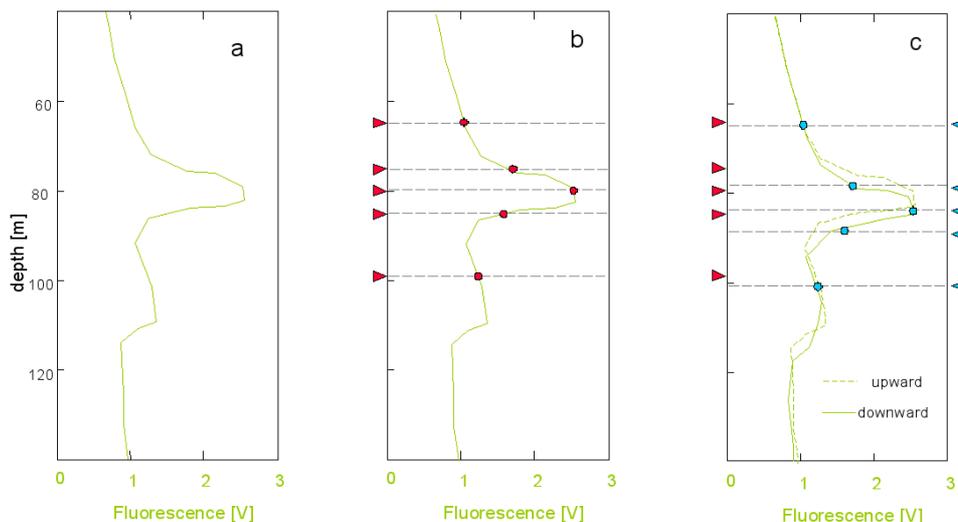


Figure 3: Example of profiler with the proposed reactive behavior. The type of data is not relevant in this case, as it is just a theoretic example. (a) Going downwards, the profiler characterizes the water column through low resolution sampling. (b) Data are processed, and interesting depths (according to predefined rules) are determined for high resolution sampling on the way back up. (c) Going upwards, the water column properties could be different from the first profile, so the system, while planning for the high resolution sampling, has to react to the changes.

4 TEST BED

An excellent place to implement and test this kind of network is Alfacs Bay (Figure 4), Tarragona, Spain. This is a bay with a rhomboid shape of 11 x 5 km, a maximum depth of 7 m, an average depth of 3 m and a total water volume of $1.5 \times 10^8 \text{ m}^3$. It acts as an estuary where fishing and seafood farming are the main economic activities and the appearance of HABs has economic negative effects. At times the bay must be closed because of HABs and the production is lost. A long term monitoring can be used to improve the understanding of the bay dynamics, while the small scale, high frequency sampling can help to detect and prevent the HABs damage and to study small scale phenomena.

The planned first phase of the project will consist of the deployment of a central node, which will be connected to a land observatory, plus two other nodes connected to it. This land line will provide energy supply and a communication channel to all the network. During the next phase, additional nodes will be added for higher spatial resolution. The proposed sensors to implant on the nodes are: conductivity sensor, temperature sensor, fluorometer, acoustic doppler current profilers (ADCPs) and hyperspectral sensors.

The sensors could be attached to vertical profilers or be fixed, close to the sea floor. They will provide information about physical and biological processes of the bay and the information they will collect could be useful for both scientific research and economic activities (e.g., detection of poisonous algae on seafood farming regions).

5 CONCLUSIONS

The work presented represents a new research line in which artificial intelligence techniques are starting to be introduced in the design and implementation of sensor networks for shallow, marine zones. The adoption of problem-specific, environmental, knowledge-based systems, in particular, could provide a qualitative and quantitative improvement in different aspects, but primarily in the

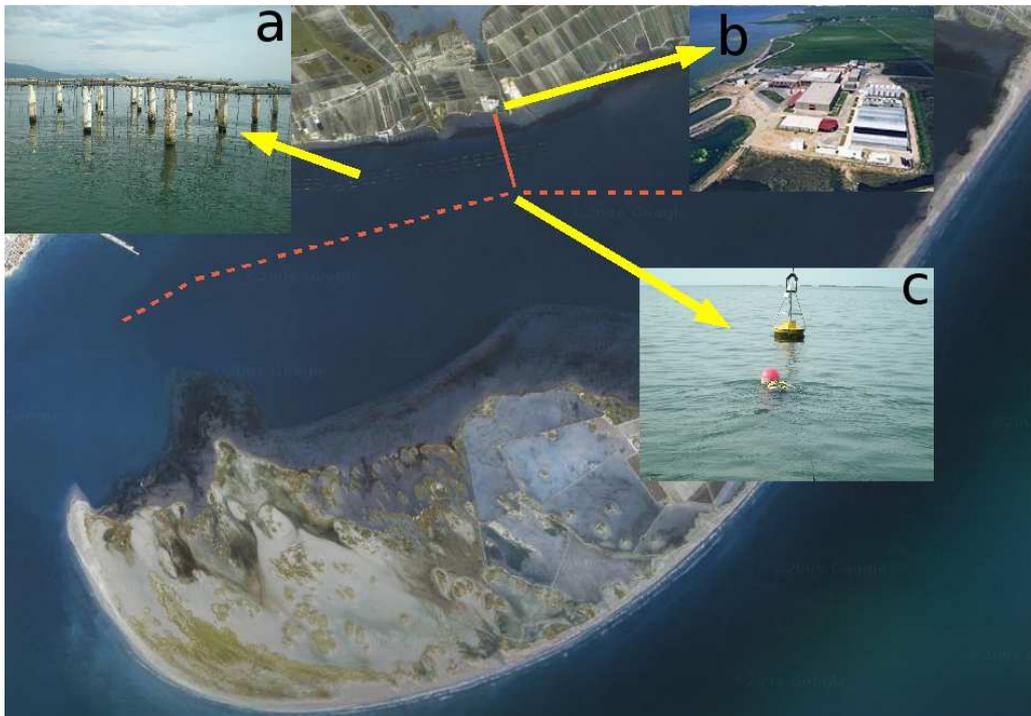


Figure 4: Proposed test bed for a sensor network at Alfacs Bay. (a) Seafood farming, an important economic activity in the region. (b) Current facilities that can act as shore station. (c) Possible emplacement of the central node, with a link to the coast.

optimization of the sampling process. We believe that the introduction of these advanced systems is essential in order to obtain intelligent, autonomous and energy efficient sensor networks. The system under development is tailored to relatively narrow environmental problems and domains, but it is applicable to a wide range of different locations and situations. Additionally, a real scenario in which to implement a network with these characteristics is proposed. The placement not only fits the environmental requirements (i.e., shallow water), but is also a region of high scientific and economic interest.

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