ENSURING RELIABLE MEASUREMENTS IN REMOTE AQUATIC SENSOR NETWORKS

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Reliable flood decision-support information systems comprise an extensive network of dependable water sensors and a bundle of accurate forecast simulations models. However, the quality of gathered data is affected by the pervasive nature of the monitoring network where aquatic sensors are vulnerable to external disturbances. Existing solutions for aquatic monitoring composed by heterogeneous sensors are unable to ensure continuously reliable measurements in complex scenarios. In this paper, we introduce a more general study of fault-tolerant sensors in the aquatic monitoring process, and we motivate the need of reliable data collection in harsh coastal and marine environments. An overview of the main challenges is presented, such as the absence of redundancy, and a framework-based solution is presented, that automatically adjust the sensors measurements from each disturbance accordingly, providing an important increase on the quality and validity of the sensor observations.

INTRODUCTION

During the last decades, private, governmental and non-profitable organizations have been developing information systems to monitor, alert and manage environment-related emergencies [1]. Platforms, such as flood emergency alert and warning systems [2], comprise an extensive network of sensors, a bundle of forecast simulations models, and decision-support modules that rely largely on a robust and reliable perception of the conditions of the physical monitoring environment. Sensors provide this insight of the real world, where the notion of continuous time and continuous values of implicated phenomena meet the computerized notion of discrete model of time and discrete estimation of the real data.

Complex and powerful forecast systems are now able to predict water levels or to track storm events with low errors, but they depend on a continuous confirmation with data. Real-time monitoring data, such as surface water elevation, flow or precipitation depend solely on the sensor hardware deployed at the water bodies (oceans, river, lakes, etc…). The goal of this paper is to propose a framework to increase the validity of the information provided by these sensors.

RELATED WORK

A cascade of uncertainties present in each part of the emergency management system affects a reliable alert and response [3]. The temporal notion and even quality of sensing data, which is used greatly in the forecasting procedures, is affected by the pervasive nature of the environment where aquatic sensors are deployed. Thus, information provided by sensors is vulnerable to external disturbances affecting its accuracy [4-6]. In water-related emergency systems, inaccurate information in aquatic monitoring may not be critical for safety within the time frame of other types of monitoring, such as aeronautics, but a possibility of an incorrect forecast may incur in issuing false warnings or not issuing real warnings in damaging situations (for instance floods or pollution events).

Existing solutions for aquatic monitoring are composed by a set of heterogeneous sensors [7], most of which vulnerable to the unpredictable natural conditions of a harsh environment. It is important to realize that due to many plausible reasons water-related sensors are unable to always ensure dependable measurements. Dependability of sensor is taken here as a high probability of sensors behaving according the requirements.

The notion of dependability introduced by Laprie [8] declares that it is "the measure in which reliance can justifiably be placed on the service delivered by a system". So, in order to understand if a system is dependable one must learn about the potential reasons for imprecise actions and what are the means to overcome it. The goal is to establish a way to state the level of dependability desired and evaluate if it was achieved.

Besides the notion of dependability, Laprie studied the impairments to a dependable system and categorized them into three facets: fault, error and failure. The latter category is the most commonly used to characterize a violation of the expected correct behavior but, although one may say that designing a dependable system is all about preventing failures to happen, one must understand that a fault is the process that leads to a failure and that the failure is the visible external effect of an error. In order to achieve dependability one should sever the chain that goes from a fault to a failure. To do so dependable systems use strategies that include *fault removal*, *fault forecasting*, *fault prevention* and/or *fault treatment* schemes. These strategies are either for stopping fault events from happening or, despite the occurrence of one or more faults, to block their effect (failures), thus making the system *fault-tolerant*.

When focusing on dependable monitoring networks, the main approach to fault-tolerant sensors is through redundancy, using a set of monitoring data from various sensors, often referred as sensor fusion.

Sensor fusion compares a set of observations from different sensors in the same monitoring area. Through processes of comparison, combination and/or smart voting schemes between sensors it is possible to conclude what should be the corrected observation and what are the faulty sensors [9-11]. When addressing aquatic monitoring and specifically the harsh conditions or broad scales, such as in maritime areas, the interested entities and users generally prefer to scatter the sensors in pre-identified points in the monitored water body according to expertise and local knowledge, to cover the most extensively the complex water dynamics. While conceptually correct, this approach makes it difficult to compare sensor observations relating ones sensor measurements to another that is placed hundreds of meters apart. Besides the distance factor, aquatic monitoring networks are usually comprised of the costly sensors [12], not easily feasible to have more than one in a confined area.

Besides the harsh conditions of aquatic environments, sensors alone have technical limitations, specially focusing on replication of data. Firstly, sensor fusion techniques assume

that a faulty measurement (thus faulty sensor) will be detected as an outlier that exceeds conclusively the estimated boundaries of the other sensor' measurements. The downside is that in a transducer (electronic/mechanical component of a sensor) the translation from analogical phenomena to the digital world has an intrinsic noise and complex failure mode [13] that becomes an obstacle when trying to distinguish between a correct or faulty behavior. Secondly, in a multi-sensor approach it is assumed that all measurements are available at the same time but heterogeneous sensors networks imply that each sensor has different sampling properties. Even if the sampling rate is the same the values may not be accessible in syncronized instants in time [9].

Considering that redundancy is the path to build and develop dependable sensors, other approaches have been applied:

a)   *Model-based redundancy*: with the help of simulation/mathematical models of the aquatic system it is possible to obtain values to validate the measurements. Isermann [11] was a big promoter of this type of redundancy where the system model calculates the measure variable and then it is compared to the sensor measurement.

b)   *Signal analysis*: it is used to monitor parameters such as signal noise, frequency response, velocity of amplitude change among others, and modulates the transducer behavior [14]. It is a robust approach in case of strange behavior in a controlled system. If a value changes significantly, then a sensor is classified as faulty (or the monitored system has changed).

The main goal of the work herein presented is to address the subject of dependability in general and then apply it to sensors. Most of the research introduced was on computer science and electronics area where systems are well defined and they handle specific problems. One of the goals of this paper is to show how we have to combine and improve all these approaches in a general fault-tolerant framework to sensors in real and complex environments such as aquatic bodies.

AQUATIC SENSORS FAILURES AND CAUSES

The study of the criticality of the sensor' observations and its affecting variables begins by analyzing the main challenges in architecting a dependable solution to the already operational sensors that are currently on-field monitoring. The design of a fault-tolerant framework requires an analysis and classification of typical aquatic sensor failures. This step is necessary to determine an effective fault detection strategy identifying its causes and the properties of the failure types. When designing a sensor the optimal strategy would be to detect and correct the fault events at its origins (transducer or software components). But when designing a framework to deal with the failures of commercial, hetereogeneous and/or already deployed aquatic sensors one has to analyze how sensor faults affect its measurements and what are the main external disturbances that cause the fault events.

External factors

Despite the fact that wireless sensors have ensured a secure position as a solution for a wide range of applications, such as the harsh environments of battlefields and disaster relief areas, it doesn't mean that these solutions are still applicable when subjecting the same reliable sensors to the unfriendly conditions observed in the water context. Water can have a severe impact on the operation of sensors. The effects of water, in particular in areas of highly variable salinity or

harsh contaminants presence, on sensor devices and on the different characteristics of waterproof sensors needs more research [15]. Flood emergency management systems are one of many applications of aquatic sensor networks, that necessitates the sensors to either reside under the water surface permanently or temporarily, for long periods.

Sensors may have technological limitations but wireless aquatic sensors have another set of additional constraints [16]: *power lifetime*, power is not often available and batteries have limited lifetime; *sensor hardware compatibility*, mostly due to data loggers and sensor nodes; *reliability*, the harsh weather conditions may cause failures in the measurements and in the wireless communication over the monitoring network; and *long-range communication*, measurement locations are commonly sparse over large areas.

As mentioned above, the design of the fault-tolerant framework for aquatic monitoring should start by the study on the influence of external factors related with the involved environment on the sensors behavior, more specifically on the sensors measurements and the occurrence of faulty measurements. The obvious factors that may have a negative influence in the aquatic sensors are the natural environmental events, particularly meteorological events such as storms (strong winds, heavy rain and/or big waves). Other not negligible factors are marine life (biofouling). In water bodies there are many algae and small organisms that can attach easily to a sensor and affect it. For the purpose of demonstration, we used the historical data of LNECs aquatic monitoring network [12] and chose two arbitrary instants in time that show the sensor working correctly and after the events the sensor showed faulty measurements.
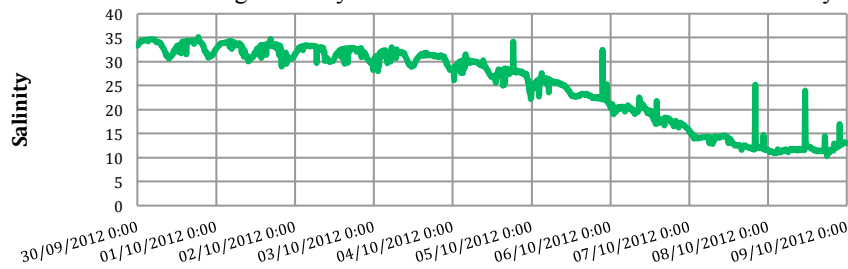

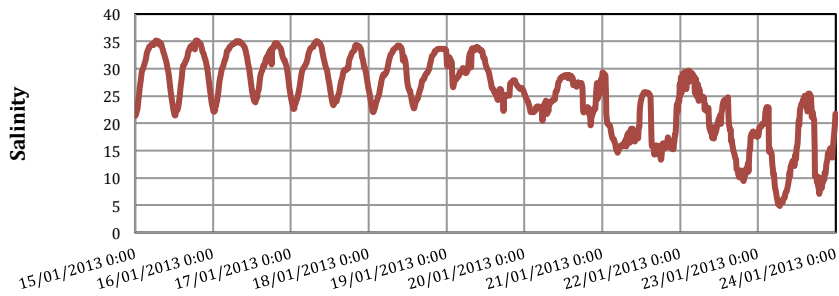Fig. 1. First detected event of sensor measurement external interference.

Fig. 2. Second detected event of sensor measurement external interference.

A first period of interferences in the measurements, a continuous and abnormal reduction of salinity values, was identified in October 2012 (see Figure 1), when no significant meteorological events intervened. In this case, the cause was the estuarine/coastal life growth localized inside the sensor casing. A second period of interferences was identified since January 19th, 2013 (see Figure 2), when a powerful storm hit heavily almost the entire Portuguese coast, a week after sensor maintenance operations were made.

We will consider a more profound overview of these types of events in the future, in order to perform a correct modeling of the impact of weather events and conditions and aquatic-related interferences as a cause of faulty measurements.

Failure modes

Table 1. Aquatic sensors failure modes
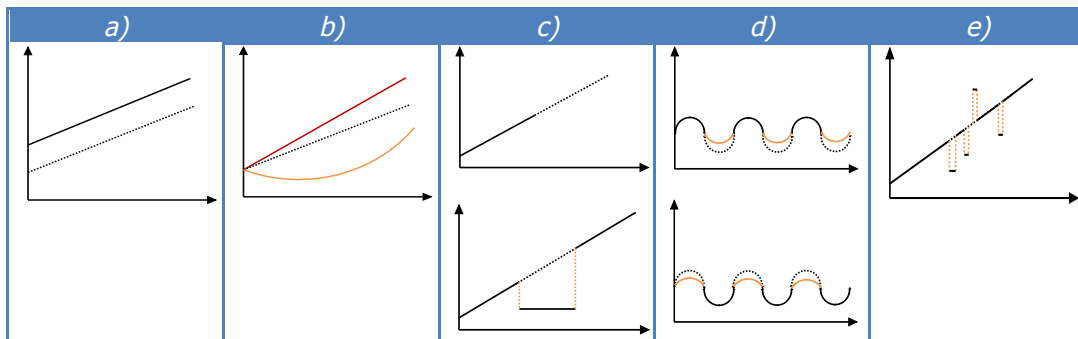
When a fault event occurs, the faulty measurement is the observable failure. The design of a framework that will ensure dependable measurements starts by the fault model of the sensors as perceived by those who will use monitoring data. Table 1 illustrates how a fault can affect the sensor measurement. In each illustrated failure mode the faulty measurements are compared to expect correct behavior, corresponding to the dashed line. Possible failure modes are:

a) *Constant or Offset failure mode:* the observations are continuously deviated of the expected by a constant offset value Y. The corrected observation would be the subtraction of offset Y to the faulty measurement;

b) *Continuous Varying or Drifting failure mode:* the observations deviate from the expected in a curve movement F(original O, expected E). To correct this type of failure mode, redundancy is obligatory;

c) *Non-existing or Jammed failure mode:* an external disturbance of accentuated gravity may cause the sensor to get jammed in non-related value. Or it can causes the sensor to crash and not providing any measurements temporarily or indefinitely;

d) *Trimming failure mode:* can either trim Up or Low – the observations pattern is the same of the expected but due to fault event, the observations can't reach the same minima or maxima than expect correct behavior;

e) *Outliers and Noise failure mode:* these faults are either sporadic or high frequent in the temporal domain and stochastic in the value domain [17].

DEPENDABILITY FRAMEWORK

If the first step to dependable measurements is the study and analysis of sensor failures and its causes, the second step would be the development of solutions to automatically adjust the sensors measurements for each disturbance accordingly, thus contributing to an important increase on the quality and validity of the measurements.

The architecture proposed herein adds one layer in the post-"sensor measurement" state. This layer will track the observations and provide a corrected observation and the observation

validity, through a set of assessments and corrections. These two outputs are complementary to the initial input (raw sensor measurement) and increase the value to the monitoring data quality (see Figure 3).
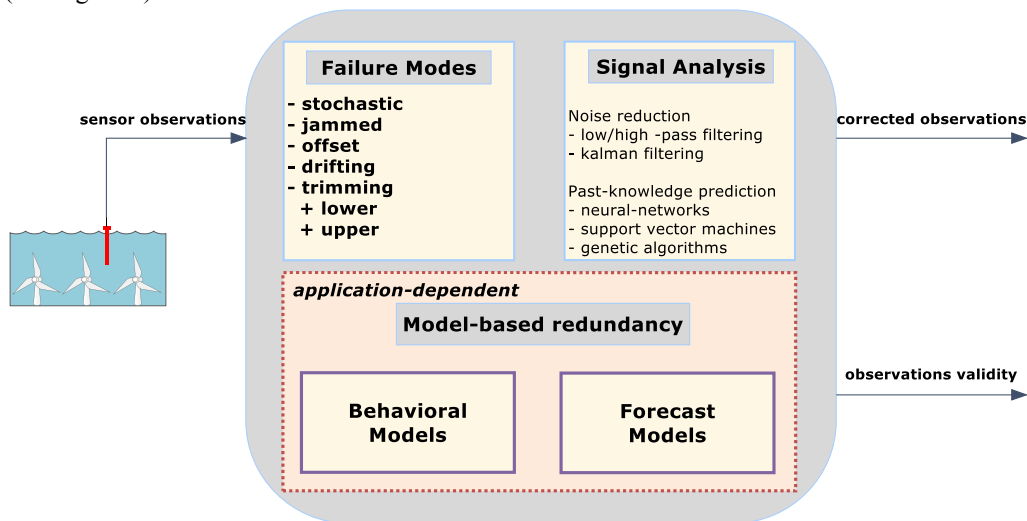

Fig. 3. General overview of dependability framework for aquatic sensors

Depending on the failure modes several processes of validation and correction are available. For instance, the faults in the *outliers and noise* category are easily corrected with "blind" (no previous knowledge) signal filtering techniques such as kalman, low-pass and high-pass filters that improve measurement precision and reduce the noise of the analogic-to-digital components. The problem in this procedure, correcting the observations without context knowledge on the variables involved, is the already mentioned lack of redundancy. Faulty measurements that fall on failure modes b), c) and d) are impossible to detect without redundancy. Moreover properties such as if sensor crashed or just didn't communicate the measurements during some temporal interval become unlikely to be confirmed. So, model-based redundancy has to be considered in order to evaluate properly the validity of the sensor observation and to correct it.

Many studies in the past decade include prediction models involving artificial intelligence [18] as a solution for smart fault-tolerant sensors. The main reason is that these methods achieve high accuracy rates on predicting the next monitoring value, based solely on past observations. Techniques such as neural-networks, support vector machines, genetic algorithms and Bayesian networks are among the best. One of the advantages on exploiting these tools in the dependability framework is the low time-consuming computational algorithms, ideal when addressing sensors with high-frequency sampling rates. The cons is that, in high-variable environments, such as oceanic and coastal, the range of the sensor observations may vary to scales that past measurements didn't reach, thus these prediction algorithms wouldn't be as accurate as the numerical model-based solutions.

Setting back the problem mentioned in the previous section: if there is only one sensor in a specific water body, measuring one or more parameters in one region, without other sensors to compare observations, how to solve the redundancy problem? Our solution adds the knowledge of the dynamic processes involved in the aquatic system. This context information is in the form of either *i)* a validated computational/numerical model that simulates the (hydro)dynamics of the water body and provides forecast results for the monitoring points, or *ii)* a simplistic pre-

determined behavioral model that, instead of forecasts, provides insights on what should be the measurements progression (behavior) along time, without predicting actual values (see Figure 4).

The application of first type of models to a water body is completely *site*-dependent, (although these simulation models may be used for any region through specific calibration), most of the computational algorithms are complex, computer-processing demanding and require calibration for the sensor position (for instance the SELFE model [19]). The outcomes are the most accurate of all the techniques presented herein since these types of models consider all processes that affect the aquatic system.

The behavioral models are a simple solution when no calibrated hydrodynamic models are available for a determined sensor *site*. The goal is to exploit the typical behaviors of the monitored parameters (see Figure 4) and check if the range and variability of the measurements are within adequate boundaries, taking into account the specific processes at stake at that site. Due to the specific differences on behaviors related to the monitored area, these are also *site*-dependent.

Fig. 4. Typical behavior of sensors measuring elevation, salinity and temperature
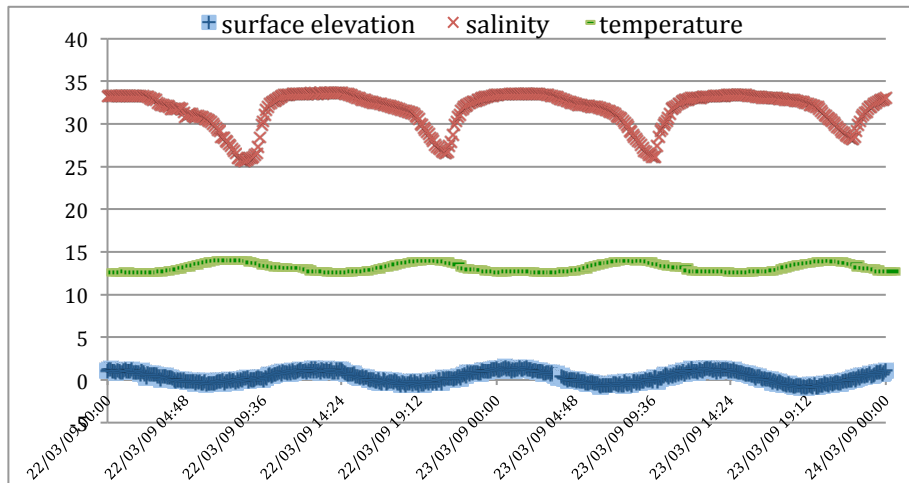
CONCLUSIONS AND FUTURE WORK CONSIDERATIONS

The paper presents the current status of an on-going research for the development of a framework that will support the dependability on aquatic real-time monitoring and forecasting systems. It started with the study of the influence of external factors related with coastal and marine environment on the sensor network behavior, more specifically on the sensors measurements, and it is now progressing to the design of the dependability framework. However, much has to be done in studying all aspects of the criticality of the sensor in the monitoring process and evaluating individually the techniques and algorithms presented to understand its effectiveness in already deployed aquatic sensor networks. Future work will include the study of a comparison of the real impact of data fusion provided by the dependability framework and the results obtained with sensor fusion, and validate the framework using both conventional (water level, salinity, temperature) sensors and recent, complex sensor units, based on spectra (e.g. spectophometers used to detect combined sewer overflow discharges).

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