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A localized algorithm for Structural Health Monitoring using wireless sensor networks

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ABSTRACT

Structural Health Monitoring (SHM) has been proving to be a suitable application domain for wireless sensor networks, whose techniques attempt to autonomously evaluate the integrity of structures, occasionally aiming at detecting and localizing damage. In this paper, we propose a localized algorithm supported by multilevel information fusion techniques to enable detection, localization and extent determination of damage sites using the resource constrained environment of a wireless sensor network. Each node partakes in different network tasks and has a localized view of the whole situation, so collaboration mechanisms and multilevel information fusion techniques are key components of this proposal to efficiently achieve its goal. Experimental results with the MICAz mote platform showed that the algorithm performs well in terms of network resources utilization.

1. Introduction

Recently, there has been much interest in the use of WSNs [1] in the fields of exploration and distribution of the oil and gas industry as well as in the renewable energy sector, particularly in wind farms, with the purpose of Structural Health Monitoring (SHM) [2]. The monitoring of physical structures enables damage prediction (fractures) and, therefore, repairs anticipation thus avoiding accidents. In applications built for that purpose, the sensor nodes are used to perform measurements of the structure which is affected by external events, delivering such measures to a data collection station, the sink node. In this context, WSNs enable the remote **monitoring** of structures to determine physical integrity through *in situ* data **collection** and **processing**.

This work proposes a localized algorithm, called Sensor-SHM, to detect, localize and indicate the extent of damage on structures belonging to environments like offshore oil and gas industry and wind farms, making use of WSNs for a SHM system. The topology of the WSN is assumed to be hierarchical, where sensors are grouped into clusters and each cluster is managed by a cluster-head (CH). The key idea of our work is to fully distribute the procedure associated with the task of monitoring a structure among the sensor nodes in a WSN, so that through collaboration among the CHs it is possible to detect, localize and determine the extent of damage. Unlike other approaches [3,4], all the SHM processing of our proposal runs inside the network (in-network processing) without any help from the sink node. When distributing the SHM processing inside the network, our work strongly takes advantage of using information fusion techniques, whose immediate benefit is the reduction in the amount of data to be transmitted back to the sink node for further analysis. Consequently, less energy is spent due to transmissions, enabling the use of communication and energy resources for performing analysis and taking decisions within the network. In our proposal, we make use of a terminology reviewed by Nakamura et al. [5] regarding information fusion techniques applied to WSNs. Such terminology was originally proposed by Dasarathy [6] in its Data–Feature–Decision (DFD) model. The terminology points three different abstraction levels of the manipulated data during the fusion process: *measurement*, *feature* and *decision*. The whole process considered in our proposed algorithm can be classified as a *Multilevel Fusion*, since it acts in the three existent data abstraction levels.

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This work builds on our previous work [7], introducing several enhancements on it. The main contributions of our previous work are: (i) we introduced the core of the algorithm with no specific foundation, which could help to better understand the algorithm operation, and (ii) several experiments to evaluate the consumption of energy resources from the network were performed. We augmented our previous work with the main following contributions, discussed in this paper: (i) we provided a foundation for the proposed algorithm that relies on the information fusion theory, (ii) several new experiments were performed concerning the precision of our damage localization mechanism, and (iii) a comprehensive analysis on the use of communication resources in the algorithm was provided.

The remainder of this paper is divided as follows. Section 2 presents an overview of Sensor-SHM algorithm. Section 3 depicts related works. Section 4 presents a motivational example based in the practical experiment seen in [8] and discusses the applicability of the algorithm. Section 5 presents the algorithm, discussing and detailing its procedures. Section 6 details the experiments performed to evaluate Sensor-SHM algorithm and the obtained results. Finally, Section 7 concludes this work.

2. Overview of the algorithm

The diagram in Fig. 1 presents an overview of the proposed algorithm, Sensor-SHM, and its procedures. In this diagram, the roles of sensors and CH nodes are summarized, and the setup procedure and data collection stages are presented separately.

After the execution of a setup procedure (Procedures 0–4), each sensor node acts in the data abstraction level named *measurement,* delivering the first useful features to its respective CH. Each sensor is responsible for sensing the structure during a *data collection stage* (Procedures 5–16), which starts from the sink node through the transmission of messages to the CHs, which request the sensing of the structure by the sensors in their respective clusters (Procedures 5 and 6). Then, each sensor node acts collecting the acceleration measurements in the time domain, relative to its physical position (Procedure 7). After that, a Fast Fourier Transform (FFT) is performed by each sensor over the collected acceleration signals (Procedure 8). Such transformation corresponds to the information fusion technique classified as a *Data In–Data Out* (DAI–DAO). Next, a method for extracting frequency values from the peaks of the power spectrum generated by the FFT is used (Procedure 9), which can be composed of a moving average filter (another example of DAI-DAO information fusion technique, where the input is the power spectrum, and the output is the smoothed power spectrum) and the peak extraction algorithm itself, applied on the smoothed power spectrum. This peak extraction algorithm is an information fusion technique classified as a *Data In–Feature Out* (DAI–FEO), since the extracted peaks are the first features which are considered useful to describe the structural health state and can be efficiently manipulated among the sensors. The frequency values obtained in each sensor refer to the first peaks of the power spectrum returned by the FFT, and will make up the signature of the structure. It is important to mention that for each sensor the initial signature of the structure is obtained from its current position in the beginning of the structure operation, i.e., at time zero, and is transmitted, during the network setup procedure by the sensor to its CH (Procedure 3). This signature is used as a reference for the undamaged structure. At later stages, each CH also receives the subsequent signature of the structure of all the sensors in its respective cluster (Procedure 10).

CHs are responsible for performing the damage detection and determining the damage location and extent through the calculation and analysis of damage coefficients (Procedures 11–14). The CH, after collecting the signatures from all sensor nodes of its cluster, performs a comparison (considering a given tolerance degree) between these values and the respective initial signatures from the respective sensors, to check whether the structure is damaged or it has been temporarily changed due to some external event. At this point, the CH starts its own sequence of information fusion procedures, acting in two levels of data abstraction (*feature* and *decision*).

The presence of damage on a structure can affect both higher and lower frequencies, in a given sensor location, depending, respectively, if the sensor is located close to the damage or not [3]. Knowing that changes in the frequencies of the higher vibration modes mean changes in local vibration modes, each CH analyzes the signatures of the sensors located in its cluster in search of changes in these frequencies. In each CH and for each data collection stage, this analysis is performed with the help of a damage indicator coefficient ($D_{i,t}$). The value of $D_{i,t}$ indicates how close a given sensor location is to the damage site. This first damage coefficient is the result of applying a *Feature In–Feature Out* (FEI–FEO) information fusion technique. A second damage indicator coefficient for the cluster ($C_{j,t}$), which depends on the $D_{i,t}$ coefficients obtained for each sensor from the cluster, is set to indicate how close to the damage the cluster is as a whole. In this last technique, a *Feature In–Decision Out* (FEI–DEO) information fusion technique, each CH node compares its cluster damage coefficient with a tolerance, which is differently set for each CH depending on the specific features of the places where the cluster was installed. When the cluster damage coefficient exceeds the tolerance, the CH node should send a message stating the value of its coefficient to its immediate (single-hop) neighbor CHs (Procedures 13 and 14). In

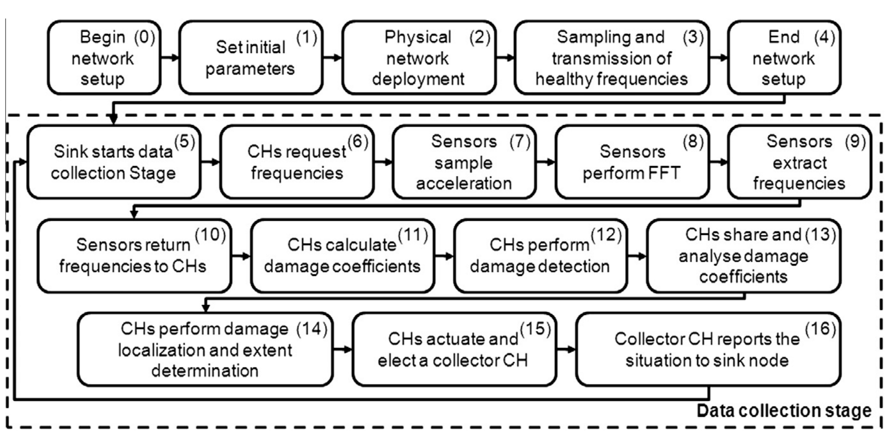

Fig. 1. Overview of the proposed algorithm and its procedures.