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Wireless and real-time structural damage detection: A novel decentralized method for wireless sensor networks

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ABSTRACT

Being an alternative to conventional wired sensors, wireless sensor networks (WSNs) are extensively used in Structural Health Monitoring (SHM) applications. Most of the Structural Damage Detection (SDD) approaches available in the SHM literature are *centralized* as they require transferring data from all sensors within the network to a single processing unit to evaluate the structural condition. These methods are found predominantly feasible for wired SHM systems; however, transmission and synchronization of huge data sets in WSNs has been found to be arduous. As such, the application of centralized methods with WSNs has been a challenge for engineers. In this paper, the authors are presenting a novel application of 1D Convolutional Neural Networks (1D CNNs) on WSNs for SDD purposes. The SDD is successfully performed completely wireless and real-time under ambient conditions. As a result of this, a *decentralized* damage detection method suitable for wireless SHM systems is proposed. The proposed method is based on 1D CNNs and it involves training an individual 1D CNN for each wireless sensor in the network in a format where each CNN is assigned to process the locally-available data only, eliminating the need for data transmission and synchronization. The proposed damage detection method operates directly on the raw ambient vibration condition signals without any filtering or preprocessing. Moreover, the proposed approach requires minimal computational time and power since 1D CNNs merge both feature extraction and classification tasks into a single learning block. This ability is prevailingly cost-effective and evidently practical in WSNs considering the hardware systems have been occasionally reported to suffer from limited power supply in these networks. To display the capability and verify the success of the proposed method, large-scale experiments conducted on a laboratory structure equipped with a state-of-the-art WSN are reported.

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1. Introduction

Aging of civil infrastructure is inevitable as they are widely exposed to short term and long term damage during their lifecycle [1,2]. While the inspection of civil engineering infrastructure has generally been difficult and costly due to their large size compared to other engineering structures, the traditional structural damage detection (SDD) methods of civil infrastructure rely heavily on frequent visual inspection [3–5]. However, visual inspection is not economical particularly when the targeted structural members are difficult to reach and/or blocked with other structural and/or non-structural elements [6,7]. The visual inspections have evolved into "monitoring" in time and researchers have been continually working on developing more feasible SDD methods in the area of structural health monitoring (SHM) ever since [8].

Sensor units are imperative for monitoring the health of civil infrastructure [9–11]. Traditionally, wired sensors have been used in SHM applications due to their availability in the market before the wireless ones [12,13]. The use of wired sensors for SHM of large structures was found challenging due to various hardships in installation and maintenance of the wiring system [14]. Following the advancements in the sensor technology, wireless sensor networks (WSNs) have been progressively utilized in SHM and SDD [15–24]. However, there are some challenges regarding the use of WSNs in SDD [25–27]. Most of the damage detection approaches available in the literature are centralized as they require transferring data from all sensors within the network to a single processing unit in order to evaluate the structural condition [28,29]. Such methods are indeed feasible for wired SHM systems [30]; however, transmission and synchronization of huge amounts of data in WSNs have been reported to be problematic. Therefore, the application of centralized methods with WSNs can be burdensome [31]. Another challenge is that wireless sensor units usually have limited power supplies [32].

A big portion of the vibration-based SDD methods available in the literature require a three-step process: data preprocessing, feature extraction, and feature classification [33]. The feature extraction is simply extracting damage-sensitive features from the preprocessed vibrations [34]. Feature classification stage involves utilizing a certain classifier to classify the extracted feature in order to figure out whether they belong to the undamaged or damaged state [35,36]. Such process requires significant computational power which is usually not readily available in wireless sensing units.

The goal of this paper is to overcome the aforementioned challenges by developing and testing a decentralized and computationally-inexpensive damage detection method based on 1D convolutional neural networks (1D CNNs). For that purpose, in this paper, the authors are proposing to use 1D CNNs on WSNs. The SDD is successfully performed completely wireless and real-time, under ambient vibration conditions. As a result of this, a decentralized damage detection method suitable for wireless SHM systems is proposed. The proposed system is tested on a large-scale laboratory structure equipped with state-of-the-art wireless sensing units. The work presented in this paper can be considered as a significant upgrade and improvement on the previous work by the authors [33,37] in which the 1D CNNs were utilized on a wired accelerometer system, under shaker excitations.

The proposed SDD system involves training of an individual CNN for each wireless unit in the WSN. In this system, each CNN is responsible for processing the locally-available data only, in a decentralized manner. This feature eliminates the need for transmitting and synchronizing the data at a central processing unit. The most compelling feature of 1D CNNs is their ability to merge both feature extraction and feature classification stages into a single block which significantly reduces the required computational time and effort. The damage detection method proposed in this paper runs immediately on the raw ambient vibration condition signals without any filtering or preprocessing. In addition, the proposed damage detection system utilizes a network of triaxial wireless units. As explained later in the paper, the CNN training process takes into account the ambient vibration signals measured along the three directions at each node of the WSN. This is done to figure out the direction along which the damage features are more pronounced.

The paper is organized in a way that a brief review of the recent applications of WSNs and CNNs are presented in Sections 2 and 3, respectively. Laboratory test setup and instrumentation are explained in Section 4. Overview, adaptation, and the back-propagation training of 1D CNNs are presented in Section 5. The proposed wireless and real-time 1D CNN-based damage detection algorithm is explained in Section 6. The experiments conducted to demonstrate the algorithm using Qatar University Grandstand Simulator (QUGS) along with the results and performance evaluation are displayed in Section 7. The conclusions are listed in Section 8.

2. Wireless sensor network use in structural health monitoring applications

It did not take long time for the SHM researchers to observe the fact that, when used in an array format, the wireless sensors can work in a network system through which the SHM processes can be run in a more practical, economical and advanced way [38,39]. The most obvious advantages of WSNs recognized in the beginning were avoiding kilometers of cable work, installation costs and associated expenses but many other advantages were identified later [40]. Yet, the WSNs had their own challenges (e.g. transmission, synchronization, limited communications bandwidth, adaptability, limited energy supply, limited memory and computational capability and etc.) on which countless studies such as mobile agent approach [41], active sensing platforms [42], smart sensors [43], reconfigurable sensors [44], eigen-system realization algorithms [45], two-tiered approaches [46], capacitance-based and impedance-based wireless sensors [47], enhanced damage locating vectors [48], zigbee technology [49], embedded goertzel algorithm [50], compressive sampling–based data loss recovery [51], operating with limited sensors [48] and many other notable work were performed to contribute to and enhance the SHM processes.