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Compressive sensing for efficient health monitoring and effective damage detection of structures

Madhuka Jayawardhana*, Xinqun Zhu, Ranjith Liyanapathirana, Upul Gunawardana

School of Computing Engineering and Mathematics, University of Western Sydney, Locked Bag 1797, Penrith, NSW 2751, Australia

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ABSTRACT

Real world Structural Health Monitoring (SHM) systems consist of sensors in the scale of hundreds, each sensor generating extremely large amounts of data, often arousing the issue of the cost associated with data transfer and storage. Sensor energy is a major component included in this cost factor, especially in Wireless Sensor Networks (WSN). Data compression is one of the techniques that is being explored to mitigate the effects of these issues. In contrast to traditional data compression techniques, Compressive Sensing (CS) – a very recent development – introduces the means of accurately reproducing a signal by acquiring much less number of samples than that defined by Nyquist's theorem. CS achieves this task by exploiting the sparsity of the signal. By the reduced amount of data samples, CS may help reduce the energy consumption and storage costs associated with SHM systems. This paper investigates CS based data acquisition in SHM, in particular, the implications of CS on damage detection and localization. CS is implemented in a simulation environment to compress structural response data from a Reinforced Concrete (RC) structure. Promising results were obtained from the compressed data reconstruction process as well as the subsequent damage identification process using the reconstructed data. A reconstruction accuracy of 99% could be achieved at a Compression Ratio (CR) of 2.48 using the experimental data. Further analysis using the reconstructed signals provided accurate damage detection and localization results using two damage detection algorithms, showing that CS has not compromised the crucial information on structural damages during the compression process.

1. Introduction

Transmitting and maintaining large amounts of data in SHM systems have been issues addressed in recent researches due to the large scale real-world structures in use. Traditionally, uncompressed structural response signals are acquired by each sensor and transmitted to a central server for processing and damage decision making. This task unnecessarily consumes one of the most valuable resource in a WSN-based SHM system – energy, and also wastes memory space of sensor nodes in both wired and wireless systems. In a wireless-based SHM system, such wastage results in reduced system lifetime and increased maintenance costs, since data transmission in a WSN is carried out at the cost of limited battery power of

* Corresponding author.
E-mail addresses: madhuka.jayawardhana@sydney.edu.au (M. Jayawardhana), xinqun.zhu@westernsydney.edu.au (X. Zhu), r.liyanapathirana@westernsydney.edu.au (R. Liyanapathirana), u.gunawardana@westernsydney.edu.au (U. Gunawardana).

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sensors. For both types of systems, transmitting a lot of data also increases the network traffic and collisions, reducing the reliability of data communication process. Even though memory is becoming cheaper, even the newest version of the most widely used commercially available sensor node – Imote2 – has only a combined memory of 64 MB. This amount of memory will barely be sufficient to a network as large as the SHM system installed on Tsing Ma, Ting Kau and Kap Shui Mun bridges in Hong Kong [1,2]. This system, known as the "Wind And Structural Health Monitoring System" (WASHMS), consists of approximately 800 sensors and operates 24 hours a day, 7 days a week, where each sensor node measures temperature, strains in structural members, wind speed deflection and rotation of the kilometres of cables in the bridges and any movement of the bridge decks and towers, generating an enormous amount of data [3].

There have been numerous proposals to mitigate the effects of these issues including decentralized data processing in SHM [4], power saving strategies [5] and data compression techniques [6]. In traditional data compression techniques, compression is applied on the already sampled signal. However, this usually leads to wastage of processing power and memory as the important information in most signals is carried only by a few samples compared to the total number of samples. The novel concept of CS appears as a potential alternative to solve this issue. By exploiting the sparsity of the signal, CS provides the means of accurately reconstructing the signal with much less number of acquired samples than that defined by Nyquist's theorem [7,8]. This concept is believed to have tremendous potential in the field of WSNs [7]. In fact, already there have been a few attempts to use this method in WSNs in the literature [9–11]. Being an application of WSN, SHM may also benefit from the compressing abilities of CS. With CS used for data acquisition in SHM systems, the energy and storage costs associated will be vastly reduced [2]. Thus, CS can be an area with high potential for research and development in the field of SHM. A preliminary study on the feasibility of adopting CS for SHM was presented in [12].

In this paper, CS based data acquisition in SHM is explored, in particular for damage detection and localization. The attempt is to preserve the energy and storage associated with SHM systems through data reduction, without losing the confidence of accurate decision-making. The effectiveness of CS for data compression in SHM is analysed using a set of experimental data from a series of impact tests carried out on an RC slab. Promising results were obtained from this application in terms of CRs and reconstruction accuracy. Further analyses on the reconstructed signal using two damage detection and localization algorithms (the ARD method [13] and the Wiener filter based method [14,15]) provided successful damage detection and localization results. The main contributions of this paper are as follows:

- Proposing the use of CS based data acquisition for reliable SHM.
- Successful reconstruction of the compressed responses.
- Comparison of the data compression performance using CS and other compression techniques.
- Successful damage detection and localization using the reconstructed responses.

The remainder of this paper is organized as follows: First, the current work in the literature on the applications of CS are discussed. Then the theory of CS is presented followed by the application of CS on the available experimental data. The success of the CS based data acquisition is analysed using the achieved CRs and the accuracy of signal reconstruction in terms of a frequency content based metric that was developed in this study. Next, a brief comparison is carried out between two other data compression techniques and CS. Finally, damage detection and localization results using the CS reconstructed data are presented followed by the conclusions.

2. Related work

CS is a quite recent development in communication and data processing technologies which has been recently introduced to WSNs. CS has the potential to serve as alternatives to both Nyquist's rate sampling and data compression techniques. Being a novel concept, applications of CS are largely under-explored in the field of sensor networks. Only a limited number of studies exist on CS in SHM applications in the literature. Bajwa et al. introduced the concept of CS for WSNs [9]. This work discusses the power-distortion trade-off associated with the data acquisition through CS in a centralized WSN, and the latency involved in the information retrieval. Then, a distributed matched source-channel communication scheme is proposed for the estimation of sensed data at the fusion center or the central server. Feng et al. investigate the problem of sensor localization in WSNs and propose a novel method called Compressive Sensing for Manifold Learning [10]. The measurement matrix for data acquisition is chosen to be the pair-wise distance matrix on which CS is applied. This pair-wise measurement matrix is constructed by each node measuring the distance to all its neighbouring nodes. A central node retrieves the compressive measurements and reconstructs the full matrix in order to construct the location map of the sensors. This work shows the high accuracy of the achieved localization results even though the distance measurement matrix is reconstructed at the central node with only a limited number of samples from the original measurement. The communication cost reduction associated with the method is also proven. A distributed algorithm for sparse signal recovery is introduced by Ling and Tian [11]. While a fraction of the sensors are turned off by a sleeping strategy, compressive sampling is performed on the awake sensors. These sensors collaborate with their active neighbours through one-hop communication to recover the compressed measurements and iteratively improve the local estimates until reaching a global maximum. The performance of this algorithm is illustrated in terms of scalability and optimal data acquisition.