SmartMonitor: Using Smart Devices to Perform Structural Health Monitoring

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ABSTRACT

In this demonstration, we are presenting SmartMonitor, a distributed Structural Health Monitoring (SHM) system consisting of smart devices. Over the last few years, the vast majority of smart devices is equipped with accelerometers that can be utilized towards building SHM systems with hundreds of nodes. We describe a scalable, fault-tolerant communication protocol, that performs best-effort time synchronization of the nodes and is used to implement a decentralized version of the popular peak-picking SHM method. The implemented interactive system can be easily installed in any accelerometer-equipped Android device and the user has a number of options for configuring the system or analyzing the collected data and computed outcomes.

1. INTRODUCTION

In this demostration, we are presenting **SmartMonitor**, a distributed Structural Health Monitoring (SHM) system consisting of smart devices. In this paper we describe the distributed system, the communication protocol, the data gathering and structural monitoring methods that we have used, as well as the novelty and advantages of using smart devices for non-typical, yet important tasks.

Paraphrasing and citing Wikipedia.org, a smart device is an mobile electronic device with connection, communication and sensing capabilities, that can operate to some extent autonomously. Over the last few years, the vast majority of the launched mainstream smartphones or tablets is equipped with a variety of sensors, including most commonly an accelerometer, a light sensor, a gyroscope, GPS, a proximity sensor and a magnetometer. Furthermore, while their price has been dropping and their popularity increasing, smart devices have several advantages that can be exploited in order to be used in various non-traditional applications, with SHM being one of them.

Some of the major advantages of smart devices are listed below. Even typical, not state-of-the-art smart devices possess high computational power. Relevant literature contains a lot of works that propose approaches for SHM using wireless sensor networks (WSN) [1]. In most of the proposed settings, micro-controllers are attached to wireless sensors. In comparison to the devices used in the traditional SHM with WSN applications, it is apparent that modern smart devices can offer much more computational power. In the typical case, a smartphone or a tablet is equipped with a dual-core CPU clocked at 1.7 GHz. This fact enables each smart device to apply CPU intensive computations using the collected data. In the past similar tasks used to run on the domain expert's base station. Moreover, the available storage and main memory capabilities are large enough to store complex data structures and all the collected data in place, even for long running experiment periods.

Moreover, high battery capacity and bandwidth are available, in contrast to wireless sensor network settings. Smart devices are always wirelessly connected to a local area network with no per-usage charge. Furthermore, it can be assumed that they have enough battery power to operate for one whole working day, as they can easily be charged, before, after or even during the monitoring experiment. Typical SHM applications that are based on WSN perform experiments that last for a monitoring period around ten minutes. Using smart devices, the monitoring period can be much longer, spanning time periods in the order of hours.

However, the biggest advantage of the wide presence of smart devices is that the needed infrastructure for SHM is already at hands of people working or residing within the structures that are to be monitored. This fact presents a chance of utilizing all this distributed computing power, while people are not using it during the day. Smart devices, as is the case with wireless sensors, can easily be placed at any location in a building, thus creating a pervasive sensing environment. Moreover, the cost and the size of highly accu-

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rate acceleration sensors is expected to continue decreasing, so it is safe to expect smart devices to accomodate ever better sensors. Studies comparing MICA motes with reference accelerometers for purposes of building risk monitoring have shown that the building risk monitoring using smart sensors is feasible, so the quality of SHM with smart devices, which is the focus of this demonstration, depends only on the performance of the embedded accelerometer [7].

In this demo we present **SmartMonitor**, a distributed system of smart devices, equipped with accelerometer sensors, able to measure micro-vibrations of civil structures. Moreover, we describe a scalable, fault-tolerant communication protocol, that performs best-effort time synchronization of the nodes, needed for accurate SHM. The protocol is used to apply a decentralized version of the popular peak-picking SHM method. Our system can easily be extended and accomodate the most sophisticated operational modal analysis techniques.

2. RELATED WORK

Most of the proposed SHM approaches in the relevant literature propose WSN protocols and ad-hoc WSNs that offer time guarantees for the data delivery and the time synchronization of the nodes. A representative work in the field is the work of Kim et al. [3], where the authors present a WSN application of SHM tested on the Golden Gate Bridge. The authors argue that their deployment was the largest wireless sensor network for SHM at the time, consisting of 64 nodes deployed on the bridge and collecting data over a maximum of 46 hops. The results were evaluated against theoretical models and previous studies of the bridge and synchronization and jitter issues were addressed. The notion of jitter represents the difference in time between a scheduled sampling action and the actual time of it happening.

In [8] Zimmerman et al. propose a distributed implementation of three popular output-only operational modal analysis techniques, namely the peak picking, random decrement, and frequency domain decomposition methods. The focus of this work is to minimize communication cost among the nodes of the WSN and maximize power efficiency. The authors deployed and evaluated their approach on the balcony of a historic theater in Detroit. This work can be considered to be the closest to ours as it implements distributed modal parameter estimation techniques in a network of wireless sensing prototypes. However, as is the case with all WSNs for SHM, the purchase of special equipment is needed, while smart devices offer computational power, sensing and communication capabilities and are already widespread.

3. STRUCTURAL HEALTH MONITORING

All structures, including civil and mobile ones, are characterized by their modal frequencies, that represent the exhibited micro-vibrations on the surface of structures exhibited in steady state. One popular method for performing vibration analysis and testing is measuring the Frequency Response Function (FRF) of the structure [9]. FRF, which is used in vibration analysis and modal testing, is a complex transfer function, with real and imaginary components, expressed in the frequency domain. It is used to identify the natural frequencies, damping ratios, and mode shapes of a structure. Conceptually, it expresses the structural response to an applied force as a function of frequency, where response can represent the displacement, the velocity or the acceleration at a specific point of the monitored structure.

Measuring natural frequencies and mode shapes leads to the identification of possible changes in the frequency response function of the structure due to several reasons, including damage caused by an earthquake or by massive flooding of the area around the building or even within the building itself [6].

SHM typically includes the following steps [3]. A structure is affected by some measured excitation that serves as the input of the system, whereby *system* represents the monitored structure. After applying the measured excitation, the oscillation of the structure is measured. The recorded values serve as the output of the system and are studied by domain experts who argue about the structural health of the system [9].

However, civil structures cannot be excited in a controlled manner. Because of this fact, only *output-only* approaches can be employed to monitor structural health. An *output-only* approach is esentially limited to only sense, store and analyze micro-vibrations of structures, without being able to measure the input forces that caused the recorded micro-vibrations.

3.1 Peak-Picking Method

Our system implements a decentralized version of the well known peak-picking method [4], which is the simplest operational modal analysis technique. Our method can be viewed as a slight modification of the decentralized approach proposed by Zimmerman et al. in [8], in that it exploits the advantages of smart devices that are able to efficiently perform complicated computations and apply even more sophisticated algorithms than the simple peak-picking technique.

The corresponding peak-picking algorithm, which is described below, computes the natural frequencies of a structure by finding the peaks of its FRF and is applied on the time series formed by the recorded accelerations in the three axes. As each node may compute slightly different peaks, due to noise or placement factors, in order to obtain the global modal frequencies of the monitored structure, an appropriate aggregation technique of the individually recorded peaks is essential.

The Frequency Response Function (FRF) of a system has been proven to exhibit extreme values around the systems modal frequencies [4]. In this sense, in our deployment we compute the FRF of the structure at each sensor location k and represent it as FRF_k. The FRF is equivalent to the Fourier spectrum of collected data, so its computation can be efficiently be performed in the smart devices. In order to compute the Fourier spectrum of the time-series formed by the collected micro-vibrations, the Fast Fourier Transform (FFT) of measured accelerations has been used. Thus,

$$FRF_{k,axis} = FFT(ts_{k,axis})$$

where $ts_{k,axis}$ represents the collected acceleration values at sensor location k along each *axis* (x-, y- or z-axis). For the FFT computation we have used the well known Cooley-Tukey algorithm, as it is employed in previous relevant studies [8, 1].

At the next step of the decentralized peak-picking method, each node k picks the p largest peaks from FRF_k. A peak is a frequency interval where the computed frequencies are significantly and consistently higher than the surrounding values, similar to the notion of bursts. Next, each node k sends the set of the selected p peaks to a central node that serves as the master of the network at the time. Finally, the central node performs an aggregation computation on the reported peaks and determines a global set of peak frequencies, which it communicates back to all nodes of the network, for fault tolerance reasons [8].

4. COMMUNICATION PROTOCOL

In this section we describe the fault-tolerant communication protocol that is implemented in SmartMonitor system. SmartMonitor is essentially a peer-to-peer architecture, where no base station is needed to collect, process and analyze the gathered data. In a brief outline, we employ a 2-tier hierarchical structure, where one node is dynamically selected as the master of the network and is responsible to collect and aggregate the results computed by its peers. Important to note is that the role of master node is just an attribute that can be held by all nodes of the network, meaning that there are no special hardware or software requirements for the master node. More specifically, all nodes hold the same information in order to recover in case of masters failure. In the following we describe our scalable and fault tolerant message-driven protocol which provides a mechanism for best-effort time synchronization of the nodes and decentralized computation of a structures modal frequencies.

When a node k wants to join the system, it sends a JOIN message to the first 254 local IP addresses, in order to identify the current master of the network. The node c that currently serves as the master responds to let node k join the network and stores its IP address. If node k does not receive a response from node c within a configured period of T_c seconds, it can safely assume that there is no current master node in the system, thus node k is the first one to join. Consequently, node k becomes the current master node of the system.

In order to perform best-effort time synchronization of the nodes, SmartMonitor implements a method similar to the synchronization technique proposed by Katsikogiannis et al. in [2]. Either automatically (every T_{sync} seconds) or manually (with user's input), the master node c sends a SYNC(t_c) message to all its peers, where t_c represents the timestamp of the master's clock at the time when the SYNC message was sent. Once node k receives the SYNC(t_c) message at time t_k according to its clock, it computes the difference $\Delta_{ck} = t_k - t_c$ and stores the result. There is an inevitable time syncronization error Δ_{te}, due to network and software latencies. This Δ_{te} can be minimized if the above procedure is repeated until the computed difference converges and does not change significantly.

When the initialization procedure finishes, new node k and master node c exchange information describing the state of all peers in the network. The state of each peer currently includes its IP address, but in the future can be extended to accomodate other useful data about the SHM experiment.

Periodically, every T_p seconds, all nodes broadcast a heartbeat message in the network in order to state that they are still running and contributing to the experiment. If a node k does not get a heartbeat from node j for some period of T_{fail} seconds, node j is considered fallen. If the current master node c is detected as fallen, the node with the lowest local IP address becomes the new master.

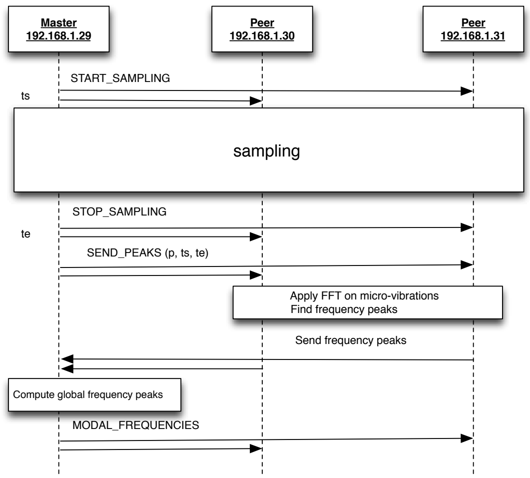

Figure 1: Sequence Diagram of the SmartMonitor system

At some time, either automatically or manually, the master node c, sends an on-demand SEND-PEAKS(p,t_s,t_e) message to its peers in order to collect the peaks that correspond to the time period between t_s and t_e. When a node k receives a SEND-PEAKS(p,t_s,t_e) message, without stopping the procedure of gathering micro-vibration data, it computes the FFT of the time-series in the period (t_s, t_e) and reports the frequency values that correspond to the p largest peaks. The procedure described above is depicted in Figure 1.

Another requirement for SHM is that sensors need to acquire data at an appropriate sampling rate for a sufficient period of time at various locations. In our experiments the accelerometers that come with smart devices have been able to achieve sampling frequencies up to 65 Hz. Sampling frequencies around 65 Hz are considered adequate enough for SHM, since they are higher than dominant modes of civil infrastructures that are usually less than 10 Hz [5]. Variance among the sampling rates of different smart devices in the network can be addressed either with downsampling, by ignoring sensor data according to the peer with the lowest sampling rate or with upsampling by polynomial interpolation.

In a realistic SHM scenario, a domain experts team would place disjoint sets of monitoring smart devices on different floors of the monitored building, as global modal frequencies may vary among different floors, especially in very high buildings. SmartMonitor accounts for this need, by letting the user manually configure her device according to the floor she resides on, thus grouping nodes by floor. Each floor has a unique master node that computes the floor's modal frequencies. An outline is depicted in Figure 2.

5. DEMONSTRATION SETUP

Equipment: We will present a testbed comprised of Samsung Galaxy Tab 2 7.0 accelerometer-equipped tablets. These Android-based smart devices are equipped with dual-core CPU at 1 GHz, 1 GB main memory and 8GB of flash storage, while their connectivity capabilities include Wi-Fi 802.11 a/b/g/n. The system is scalable and can operate even with one device that will essentially serve both as master and as

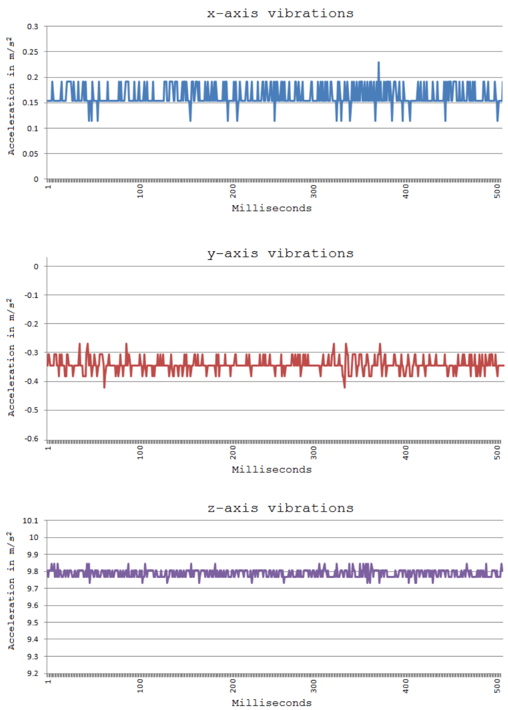

Figure 3: Micro-vibrations in x-, y- and z-axis for a monitoring period of 5 seconds.

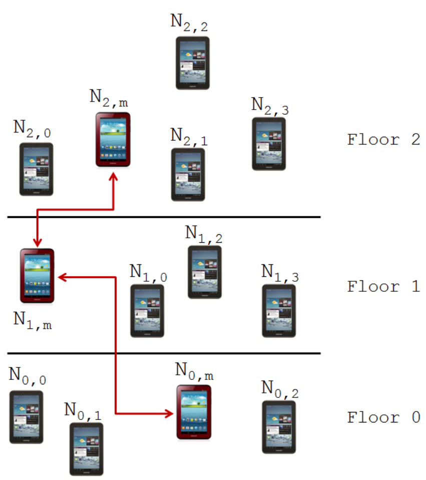

Figure 2: An example deployment of sensing smart devices accross 3 floors of a civil structure. $Node_{i,j}$ **is the** $j-th$ **node on the** $i-th$ **floor.** $Node_{i,m}$ **is the master node on the** $i-th$ **floor.**

data gathering node, but for the purposes of the demonstration we will be using at least two devices. The implemented interactive system can be easilly installed in any accelerometer-equipped Android device.

Demonstration plan: The devices will be placed on a table or on the floor and will run an SHM experiment for as long as desired by the users. During the experiment the devices will be recording natural micro vibrations of the building and computing the structure's modal frequencies when requested by the master node, while the users will be given a number of options. For the purposes of the demonstration, the users will be presented with an interactive user interface and will be able to start and stop the sampling procedure on the two devices individually, to visualize the collected acceleration data or the computed modal frequencies and to manually select the master node. All collected data and plots will be available during and after the demonstration and they can easily be exported as a database for use and analysis by domain experts. In our experiments, the embedded accelerometers have been sensitive enough to capture micro-accelerations caused by the building's natural frequencies. Figure 3 depicts the micro-accelerations measured by a Samsung Galaxy Tab 2 7.0, during a 5 seconds monitoring experiment on the 1st floor of a 4-floor building.

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