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Remote and Wireless Long-term Vibration Monitoring of Historic Monuments

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Abstract

Wireless and remote vibration long-term monitoring offer several advantages, especially to historic masonry monuments. Monetary advantages from reduced site visits and expert intervention as well as efficiency from automated and online data analysis make the system an attractive option for long-term monitoring of changes in vibration characteristics of historical monuments. Monitoring systems that are deployed for the long term using wired and cable powered sensors and computers is also impracticable at sites that also serve as tourist attractions. This paper discusses a proof-of-concepts application of a six-month long deployment of a vibration-monitoring system on a culturally important historic monument Fort Sumter in Charleston, SC. The system is designed to have a negligible aesthetic impact on the monument by using solar energy to power the sensors, radio communication between sensors and data acquisition system, and remote control over internet. The key considerations, detailed deployment experience and lessons learnt are also discussed.

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Keywords: Remote sensing; Structural Health Monitoring; Historic masonry.

1. Introduction

Historic masonry structures are part of the United States architectural heritage, history, and culture. Historic structures are especially susceptible to physical, chemical and biological processes which degrade their material and structural integrity, potentially leading to catastrophic failure. This deterioration poses a challenge to infrastructure managers and caretakers of these monuments. With limited budgets, manpower, and information, caretakers must fashion a long term preservation and maintenance schedule for the monuments.

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Vibration-based Structural Health Monitoring (SHM) provides a mechanism that can give caretakers information on assembling these maintenance and rehabilitation schemes. SHM is an established technique that provides capabilities to detect, quantify, localize and classify structural damage based on changes in structural vibration response [1]. The theoretical basis, on which SHM relies on, is that the vibration response of a structure is related to its structural properties, i.e. mass, damping, and stiffness properties. Thus, changes in these structural properties—whether due to damage or rehabilitation efforts—will result in changes to the vibration response. Vibration-based SHM relies on in-situ vibration measurements to detect these changes in system properties and relate them to the overall state of the structure [2]. Generally, data is collected by placing sensors at strategic locations within the structure [3], from which damage-sensitive response features can then be extracted to estimate damage characteristic. SHM thus has the capability to detect damage that was not caught by routine visual inspection. Although widely implemented in mechanical, aerospace and civil applications, several complications remain in the widespread applicability to historic structures due to issues related to complex geometry, difficulty in testing and modeling, and noisy data.

This paper describes the design, verification, and six-month deployment of a low-power energy-harvesting wireless sensor network on historic Fort Sumter in Charleston South Carolina. This masonry fort is notable as the place of the first battle of the American Civil War. Wireless Sensor Networks have been used for structural health monitoring [4] and specifically for monitoring of heritage structures [5-6]. This deployment is significant because 1) this is one of the longest structural health monitoring deployments for active heritage monuments in the US, 2) the system was verified against industry standard vibration sensors before deployment, and 3) the system was deployed in a very hostile coastal salt water environment. We also give practical advice and lessons learned for use by future researchers investigating structural health monitoring for heritage sites. Additionally, we have open sourced the hardware design of our sensor on our website (http://persist.cs.clemson.edu) to provide an extensible platform for wireless SHM.

2. System Design

Vibration sensing forms the first part of the structural health monitoring for damage estimation toolchain. Any errors at this stage, or noisy data generated here, is amplified further down the process, making it crucial to design a resilient, precise, and low noise vibration sensor. Our custom hardware sensor, designed using Autodesk EAGLE, is shown in Fig. 1, with the major components labelled and detailed in this section. In this section, we also briefly detail the low power software, processing and communication components, the basestation, and the remote monitoring interface.

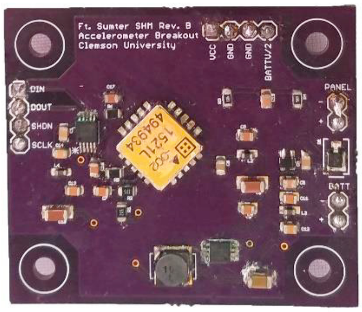

Fig. 1. This figure shows one of the single axis low noise accelerometer based vibration custom sensor we developed and deployed for structural health monitoring of Fort Sumter National Monument.

Low Noise Accelerometer: We chose an ultra-low noise ($7\mu g/\sqrt{Hz}$), high precision Silicon Designs 1521L surface mount single axis accelerometer with an input range of $\pm 2g$ and sensitivity of $2V/g$ for vibration sensing. The analog inputs to the accelerometer have a low pass filter with a cutoff frequency of $2kHz$ to filter out high frequency voltage transients that could introduce noise in the collected data. The frequency response of the accelerometer is set at $300Hz$. In addition to filtering, a stable half supply reference voltage is generated for the zero gravity reference point.

Precision Analog to Digital Converter: Most microcontrollers have on-board Analog-to-digital converters (ADC), however, these are usually low quality in terms of precision, noise, and features. We chose the Texas Instruments