Trials and Tribulations of a Sensor Networks Deployment on Fort Sumter National Monument

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ABSTRACT

Historic masonry structures deteriorate substantially over time. This deterioration is advanced by difficult environments like that experienced by the coastal Fort Sumter in South Carolina, USA, famous as the location of the first battle of the US Civil War. Landmarks like Fort Sumter are of significant cultural and national interest, and must be carefully maintained to allow visitors to understand and connect with history for many years into the future. Timely maintenance, coupled with careful degradation forecasting is required to keep these structures standing. However, in gathering structural health information that informs preservation efforts, researchers often rely on expensive, bulky, tethered sensors. These sensors have limited deployment lifetimes, and usually require constant maintenance and oversight.

In this paper we describe the system design of a network of wireless sensors that perform structural health monitoring on historic Fort Sumter over the course of a six month deployment. Using wireless sensors allows long term, continuous monitoring of structural health, helping plan preservation efforts to extend the lifetime of the structure. This deployment experience offers many valuable lessons for the community in developing successful deployments. We also detail the deployment experience, list lessons learned, and cast this system in the vision of sensing for the preservation of heritage monuments.

CCS CONCEPTS

• **Computer systems organization → Embedded systems**;

KEYWORDS

Sensing, Deployment, Energy harvesting

Figure 1: Aerial view of Fort Sumter (Courtesy: National Park Service).

1 INTRODUCTION

Historic masonry structures are part of the United States heritage, history, and culture. Heritage 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 their monuments.

Structural Health Monitoring (SHM) [2, 5] provides a mechanism that can give caretakers information on assembling these maintenance and rehabilitation schemes. SHM is an established civil engineering technique that can detect, quantify, localize and classify structural damage based on changes in structural response [5]. SHM is based on the structural dynamics concepts that the vibration response of a structure is related to its mass, damping, and stiffness properties. This means that changes in the structure—whether due to damage or rehabilitation efforts—will result in changes to the vibration response. 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 collection is achieved by placing sensors at strategic locations within the structure[9]. Damage-sensitive response features can then be extracted from this data. This data can then be used to ensure human safety, and detect damage that was not caught by routine visual inspection.

This paper describes the design, verification, and six month deployment of a low-power energy-harvesting wireless sensor network on historic Fort Sumter (shown in Figure 1) in Charleston South Carolina. Fort Sumter is a pre-Civil War Era sea fort located in Charleston Harbor, South Carolina. This historic monument is best known for the Battle of Fort Sumter, the event which began the American Civil War in 1861. The fort is a five-sided masonry structure built on a man-made sand-bar. 119 years after the initial construction of the fort began Fort Sumter was declared a national monument. Fort Sumter witnessed several battles that severely

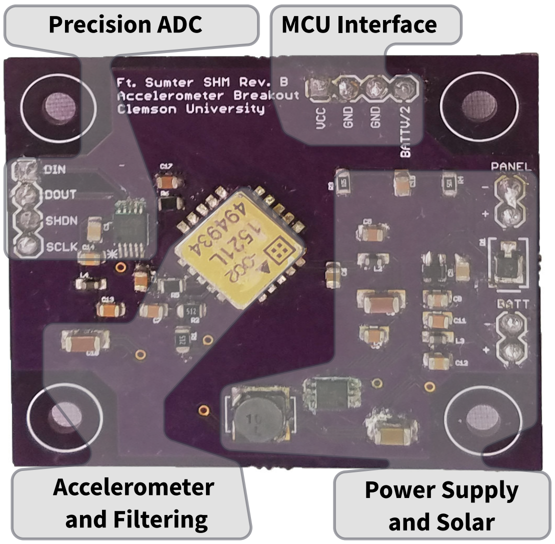


Figure 2: This figure shows one of the single axis low noise accelerometer based vibration custom sensor we developed and deployed for structual health monitoring of Fort Sumter National Monument.

damaged the structure. After several rounds of demolition and reconstruction, Fort Sumter was declared a national monument in 1948. The fort has since been maintained by the National Park Service and is currently accessible to visitors; with hundreds of thousands of people visiting the monument per year.

Wireless Sensor Networks have been used for structural health monitoring[1, 6–8] and specifically for monitoring of heritage structures[3, 4]. The deployment on Fort Sumter is interesting to the community because 1) this is one of the longest structural health monitoring deployments for active heritage monuments, 2) the system was verified against industry standard vibration sensors before deployment, 3) the system was deployed in a very hostile coastal salt water environment, 4) many challenges were encountered, from dealing with noise, to emulating deployment conditions, to working around tourist activity. In this paper we detail the deployment and give practical advice and lessons learned for use by future researchers investigating structural health monitoring for heritage sites.

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 design is shown in Figure 2, with the major components labeled 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. An overview of the entire system is shown in Figure 3.

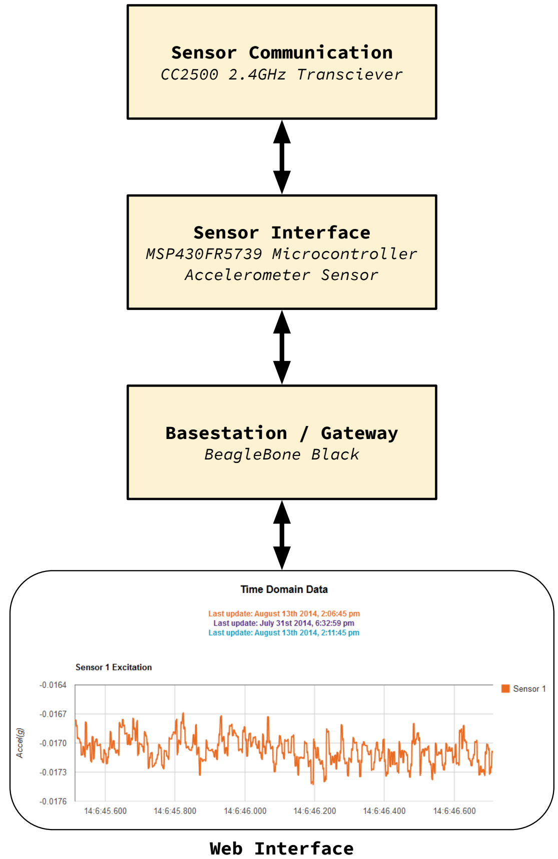


Figure 3: This figure shows the an overview of the entire system, including the sensor and communication, with BeagleBone black gateway, and the remote monitoring interface accesible via the internet.

Low Noise Accelerometer: We chose an ultra low noise ($7\mu g/\sqrt[2]{Hz}$), 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 2 kHz to filter out high frequency voltage transients that could confuse the data collection. The frequency response of the accelerometer is set at 300 Hz. 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 ADS1120 16-Bit ADC which was designed specifically for small-signal sensors. This ADC is low power even when sampling at full speed which helps extend the lifetime of the sensor. The ADC also has a programmable gain (from 1–128 V/V) that enables high resolution recording of small signals. In our sensor design we trade off high sampling rates and low costs, for high precision, low noise, and high accuracy.

Power Supply: The entire sensor is powered by a 2.4Ah rechargeable LiPo battery pack. Precision ICs like the ADS1120 and precision analog sensors like the 1521L are only as accurate and stable as their power supply. The sensor has filtering and bypass capacitance on both the 5V analog supply, and 3V logic level supply, along with isolation of switching components like the stepup regulator and inductor. Additionally a large ground plane covers both the top and bottom of the sensor PCB.

Solar Harvesting: For a long deployment, energy harvesting is a necessity. We chose a 95mm x 51mm x 3mm Sundance solar panel with 70mA short circuit current, and 7.2V closed circuit voltage. This panel was connected to the battery to trickle charge when an abundance of energy was available.

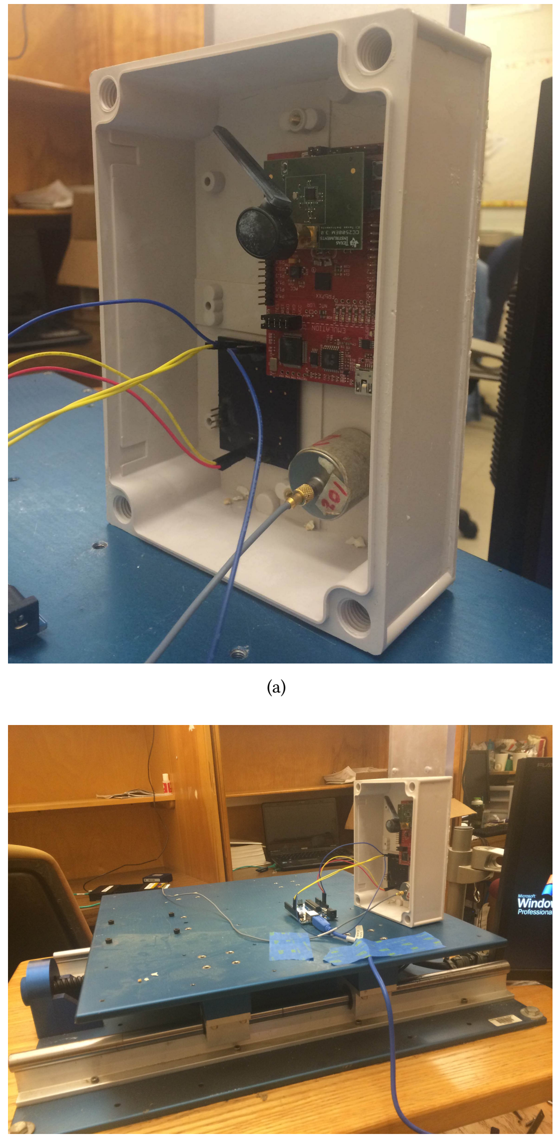
Processing and Communication: The sensor shown in Figure 2 is a daughter board that connects to an MSP430FR5739 launchpad that performs all computation, and coordinates sensing, signal processing, and data transfer to the basestation. The MSP430 uses a CC2500 2.4GHz radio transceiver for communication with the basestation. The MSP430 and CC2500 are both low power modules which enable extended battery lifetimes.

Low Power Firmware: The sensor is able to keep energy costs low by duty cycling the radio, accelerometer, and ADC. Every few minutes, the sensor wakes up from a deep low power sleep mode and turns on both the accelerometer and the ADC, allowing their reference and circuitry to settle to increase reading accuracy. Once the analog sensor is settled, the MSP430 communicates with the ADC to gather a 1000 sample long buffer of timestamped acceleration readings. This buffer is then sent to the basestation in the allotted timeslot that is assigned when the sensor first enters the network.

Basestation and Remote Access: The basestation is composed of a BeagleBone black equipped with a CC2500 radio. The basestation synchronizes the nodes, and coordinates data collection with up to 32 nodes.[1] The basestation also runs services to maintain a persistent connection and periodically transfer data to the on-campus server. The basestation uses a real time clock and boot scripts to automatically recover from power failures. A web service running on the campus server graphs the incoming basestaion data and provides important information to provide a birdâĂŹs eye view of overall system health.

3 SENSOR VERIFICATION

Before deploying our sensor in the actual environment we compared the accuracy and precision against tethered power industrial models. This was essential: Fort Sumter is an active tourist attraction, with limited staff resources to support a deployment as well as take care of everyday duties needed to support the monument operations. Very little testing could be done on sight as a consequence. We used the PCB 393B04 Seismic, miniature, ceramic flexural accelerometer for comparisons, an expensive and more accurate model than our accelerometers specifications. To evaluate the sensors, we performed a shaker table test, and impact testing. Our verification setup is shown in Figure 4, with the custom sensor



(a)

(b)

Figure 4: This figure shows the verification setup for the sensor. The module is shown in (a) which includes the MSP430FR5739, custom vibration sensor, CC2500 radio, and a high powered, high accuracy reference accelerometer. In (b) the shaker table setup is shown with the module mounted.

mounted on a shaker table. For each test, the wireless sensor and wired sensor were mounted at the same angle and direction, as close as possible to each other and with the same mounting adhesive to reduce the errors from setup.

Ambient: For the ambient testing, data was recorded for a period of five seconds without any external excitation besides general activity in a laboratory. This wireless accelerometer used in our sensor has a noise floor of ($7\mu g/\sqrt[2]{Hz}$), the wired sensors noise floor

[1]The fewer the nodes, the more data can be collected per node.

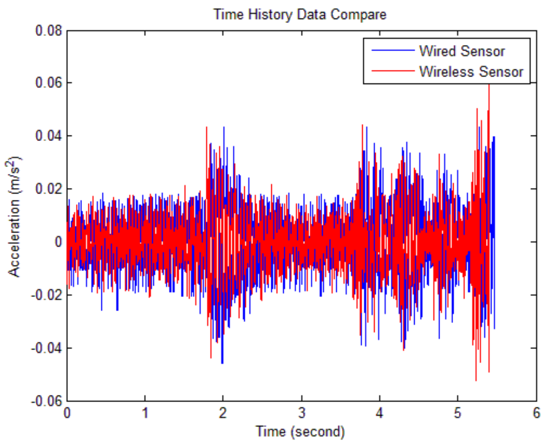


Figure 5: This figure shows wired and wireless comparison of ambient testing.

is an order of magnitude lower. Our wireless sensor did not need to meet or exceed the performance of the wireless sensor, instead, we were interested to know whether the sensors noise floor and accuracy were sufficient for detecting the ambient vibration levels of Fort Sumter. Ambient testing gives an idea of the noise floors of both sensors, if they are comparable, then the wireless sensor has an acceptable level of noise for recording data with features related to structural integrity. Figure 5 shows the time history of the two sensors; the wired and wireless. The wireless sensor closely mimics the more expensive wired sensor. As can be seen in the figure, the maximum acceleration for the wireless sensor does not match that of the wired sensor. It is believed that the wireless sensors have a better filter than the wired ones and therefore they smooth out the extreme values that the wired sensors are capturing.

Shaker Table: For shaker table testing, a random vibration input signal was applied to a shaker table that had the sensors secured on it for one minute. Data was recorded for both wired and wireless sensors. The comparison of the time history measurements from the wired and wireless sensors is shown in Figure 6. As shown, the maximum acceleration values do not match between the wired and wireless sensor. The wired sensor has a larger bandwidth than the wireless sensor (1700 Hz wired, 300 Hz wireless). The wireless sensors lower sampling rate misses peaks that the wired sensor can detect.

Impact: We also measured the responsiveness of the wireless sensor to impacts when compared to the wired sensor. The results of this experiment are shown in Figure 7. As shown, the wireless sensor closely matches the damped impact response time history recorded by the wired sensor.

Summary: The wireless sensor comparison with the wired sensor on the shaker table and impact test confirmed the data matches sufficiently well to give confidence in our data collection using a network of our sensors on Fort Sumter National Monument.

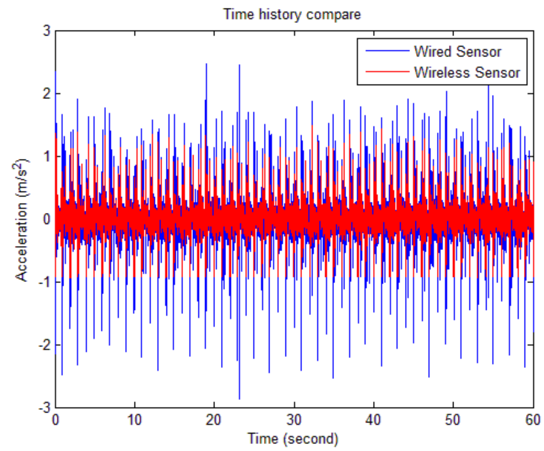


Figure 6: This figure shows wired and wireless comparison of shaker table testing.

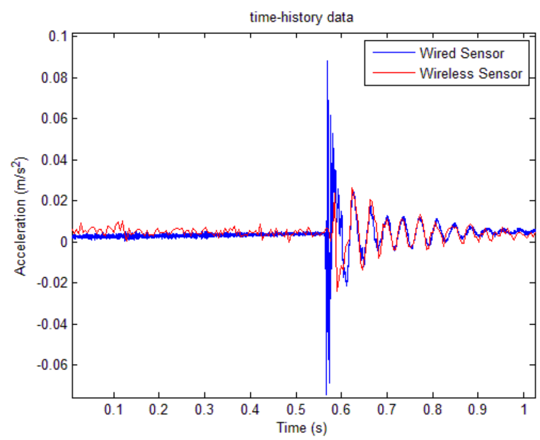


Figure 7: This figure shows wired and wireless comparison of a single impact.

4 DEPLOYMENT

We deployed three sensors on the casemates of Fort Sumter (shown in Figure 8). This region was chosen because settlement between the exterior wall and the arch pedestals was reported. Therefore this area could be a candidate for maintenance in the future.

A major constraint of our structural health monitoring deployment was that it be non-invasive to the structure. To preserve the aesthetics of the fort, we made the SHM hardware as non-intrusive as possible to public view as well as non-obstructive for people walking through the casemates. The 3 sensors were deployed out of reach (and view) of any tourists to avoid accidental damage or vandalism. Also, the hardware was protected from the elements by a air tight, water proof case that contained silica gel to wick away any moisture. The sensors were mounted using a removable adhesive that is not harmful to the masonry surface in any manner. In addition, the mounting plates that go between the sensor and the masonry surface match the color of the masonry which made the system less intrusive to view.

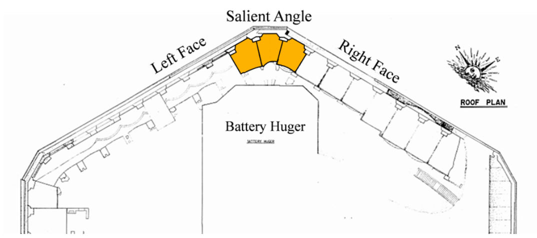


Figure 8: This figure shows the roof plan of Fort Sumter with the casemates highlighted where our structural health mointoring network was deployed on.

We deployed the basestation inside a large pelican case on top of the center building of fort sumter. This provided near line of sight between the basestation radio and the sensors, reducing packet loss. The basestation was connected with a weatherproof ethernet cable to the onsite internet of Fort Sumter, providing a mechanism to transport data from Fort Sumter to our university. This data was then processed by Matlab scripts to extract salient features.

All three sensors were deployed in early July of 2014. Data collection proceeded uninterrupted for five months until the middle of December when a power failure and extremely heavy rainstorm at Fort Sumter waterlogged the basestation and caused one of the sensors to fall, damaging its components. A new basestation was deployed and the remaining two sensors were able to gather data for another forty days before they were taken offline.

5 LESSONS LEARNED

Throughout the ideation, design, assembly, verification, and deployment of our custom sensors for Structural Health monitoring, we ran into many challenges. This section collects some of the lessons learned during this process that we hope will inform and enable future researchers in civil engineering, computer science, and electrical and computer engineering, that use wireless vibration sensors to monitor heritage structures.

Energy and Lifetime: The design of our sensor and its software was engineered towards reducing the average power draw and extending the battery lifetime. The processor chosen (an MSP430FR5739) only drew 100 μA in active mode. When sleeping, the entire sensor board only drew 3 μA, as the accelerometer, ADC, and radio are all turned off. The average power draw was dominated by transmitting (22 mA) or receiving (15 mA) over the radio, and sampling from the Accelerometer (5 mA) using the ADC (1.5 mA). To extend the lifetime we intentionally left the sensor in sleep mode for most of the time. The sensor may miss some important data, but it has a much longer lifetime to make up for this. A key part of preserving this low power function was using synchronization with the basestation to give specific time intervals where each node could communicate without interfering with another. Since the basestation was always on, it could afford to continuously broadcast the time of day, allowing sensors to synchronize with it and get instructions on when to send their data.

Temperature and Harsh Conditions: Fort Sumter was an especially harsh environment because of the high heat, salt water, and heavy rain and thunderstorms. We could not anticipate thunderstorms and flooding, high temperature however *could* be compensated for in post processing. Electrical components exhibit behavior changes when exposed to high heat. For our processor this meant data collection would happen slightly faster. To account for this, we used the on-board temperature sensor of the ADC, which was built for higher temperatures. We sent a temperature reading with each buffer of acceleration data.

Managing Error and Uncertainty: An important requirement for SHM deployments on civil structures is that the noise floors must be as low as the vibration response is low magnitude. The first step in our sensor design was identifying the sources of noise which could cause errors, and places where there were trade-offs in sensor performance (like between noise floor and energy usage). Error can manifest in hardware and software.

In hardware we made sure to consider analog sensing requirements (gravity range, number of axes, filtering needs, noise floor) and the digital needs (number of ADC bits, voltage range, logic levels, gain levels, sampling rate). Error can be introduced by misuse or misunderstanding of any of these properties. Most important in the hardware design however, was proper layout, grounding, and power supply bypassing and filtering. We put ferrite beads on each power supply (3V and 5V) and a generous amount of bypass capacitance to smooth out any voltage transients that could influence readings. We also put a large ground plane on the board, and did not crowd components, sacrificing space savings for stability.

Software has considerations for managing uncertainty as well, timekeeping being the single most important. Accurate timekeeping allows for tight synchronization with the basestation and accurate data collection. Nodes periodically received updates from the basestation, which was equipped with a very accurate real time clock (Maxim Integrated DS3231). Another important factor to consider is the percentage of time the sensor nodes should duty cycle. Our nodes spent 91% of their time (once synchronized with the basestation) in a low power sleep mode, and the remaining 9% in active mode collecting sensor data and sending it to the basestation. With the relatively large solar cell and battery deployed at Fort Sumter, we could afford a higher percentage of active time than typical sensor networks. More data collection reduced the amount of holes in the data, reducing uncertainty in our final processing.

Designing for Failure: For long deployments, failure of some kind is inevitable. We experienced node failure, basestation failure, flooding, and server power outages over the course of our deployment. Our basestation software was designed and tested for power failures. If there was a power outage and the basestation had to reboot, boot scripts automatically configured the system from scratch, starting up sensor collections, sending out synchronization packets, and establishing a connection over the internet with our university server. The basestation was also equipped with a large SD card to store sensor data if the internet connection was down. These were synced to the remote university server once the connection was reestablished.

Our node software was similarly written for resilience—but with the express purpose of conserving energy. We dedicated an internal ADC port to monitor the battery voltage. This information could be sent to the basestation for diagnostics, or used by the node itself to know if it should remain inactive to charge up. We also programmed the nodes to go into a sleep mode if basestation contact could not be established (because of basestation failure or power outage). The nodes would only wake up to listen for basestation packets a few times an hour after going into this mode, allowing them to conserve energy.

Calibrate and Test Sensors Before Deployment: Deployments are expensive and time consuming; verify as much as possible before deployment. This is especially true for small signal vibration sensing, where a board design error that increase the noise floor can render a sensor completely useless. Before we were able to deploy our custom vibration sensors we had to verify them against industry standard, wired vibration sensors. This was absolutely necessary to ensure confidence in our data; the vibration sensor is the first step in the SHM pipeline, so errors and noise magnifies at each stage. We had to design three revisions of our sensor before we finally developed the final design that satisfied noise and accuracy requirements.

Your Testbed is a Tourist Attraction: One of the major constraints of monitoring heritage sites is that ehy are almost always tourist attractions which see heavy foot traffic. This requires careful scheduling with caretakers, and limited chances for fixing mistakes during or after deployment. We specifcally had to design our sensors to be invisible to the average tourist walking through Fort Sumter. Identifying and taking these considerations early on in sensor design will simplify any deployment and reduce suprises.

Provide Remote Diagnostics: A crucial aspect of any deployment is the ability to remotely fix and diagnose sensors, as well as view incoming data in real time. This is a necessity for heritage site monitoring because 1) researchers will generally have fewer opportunities to gain access to the historic site, because of tourism and maintenance schedules, and 2) caretakers are invested enough that they want to see visual proof of the efficacy and usefulness of the approach. To enable this function we ran an ethernet cable to the basestation, allowing it to establish a SSH tunnel with a dedicated server on our university campus. This tunnel piped raw sensor data that was collected, and was synced every ten minutes. Once the data arrived at the server, it was rendered onto a web page made publicly available. This SSH connection also gave us command line access to the basestation, allowing us to inspect data, timestamps, and packets dropped to get a better idea of the health of the system.

6 CONCLUSIONS

Longterm structural health monitoring with traditional wired sensors is prohibitively expensive, time consuming, and intrusive. Wireless sensor networks have quickly become an attractive solution for monitoring as they are relatively inexpensive, are non-invasive, and allow for minimal human interference through their autonomous operation, while providing the same (or more) benefits as wired sensors. In this paper we have described a six month long deployment of custom vibration sensors for the structural health monitoring of Fort Sumter National Monument. We described the design of the low power sensor, outlined verification efforts versus a wired industrial quality vibration sensor, detailed our deployment experience, and commented on lessons learned that are applicable to future researchers. We believe that this system is a significant step towards fully autonomous monitoring of our treasured national heritage structures. These wireless sensor networks will continue to provide caretakers of these monuments with the information they need to preserve our culture for future generations.

ACKNOWLEDGMENTS

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