MONITORING OF THE ST. PAUL LUTHERAN CHURCH USING A WIRELESS SENSOR NETWORK DURING FOUNDATION STABILIZATION

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Abstract

Preserving significant buildings not only saves the structure, but it also preserves the history of the United States for future generations. The availability of a fast and cost effective monitoring system could help persuade more people to rehabilitate historic structures rather than building a new structure in its place. The main goals of this study are to develop a wireless sensor network (WSN) for the specific application of historic structures and to conduct a feasibility test in the field. The structure considered is a historic masonry church with a timber-framed roof. During the construction process, the foundations along the exterior walls are underpinned and the floors are removed and replaced with a floating concrete slab, topped with stone. Upon completion of the structural foundation work, it can be seen that the WSN is an effective instrument for monitoring of historic structures.

Keywords

Wireless Sensor Network, Historic structures, Rehabilitation, Tilt, Monitoring, Foundation stabilization, Wends, Painted Churches of Texas
INTRODUCTION

As noted in Blaise et al. (2008), “heritage sites match the interests of many in that they materialize historical influences and differences”. In an effort to preserve them for the future, historic structures are typically held to different standards and requirements which are imposed by the Secretary of the Interior’s Standards and the National Park Service. For a structure to be listed on the National Register of Historic Places in the United States, it must be over 50 years old and demonstrate that it is of historical significance. Advantages of having a structure that qualifies for the National Register include incentives such as tax credits and federal grants to assist in the maintenance of the structure. Once on the register, any treatments should follow guidelines created by the Secretary of the Interior’s Standards. Accordingly, the Secretary of the Interior’s Standards for the Treatment of Historic Properties will be a major point of reference when researching appropriate options. These standards contain both written and photographic descriptions of acceptable treatments for historic structures. As stated by Weeks and Grimmer (1995), the approach developed must not have a negative impact on the historic character of the property.

Of significance to structural engineers and preservationists alike, the development of a WSN for historic structures will increase the understanding of structures built with materials with unknown properties. This will aid in building assessment as a reliable WSN can collect data to help a structural engineer understand the current and changing conditions of the overall structure. Rather than making assumptions about material conditions or relying on small-scale tests, structural engineers will be able to quickly and cost efficiently use data from the WSN to determine the state of the overall structure.

Although some research is underway dealing with wireless sensor monitoring of historic structures, Swartz et al. (2005) claims that it is limited with respect to both effectiveness and scale. More research on the subject will aid in addressing the additional regulations imposed by the Secretary of the Interior’s Standards.

Equally as important as selecting the proper WSN is the need for more research to determine the optimal placement of sensors. Cinque et al. (2006) contends that optimal placement of sensors serves to
decrease installation cost while increasing the reliability of the network. Although research has been undertaken concerning optimal placement, very little information is available for optimal location on historic structures, which must adhere to more stringent aesthetic criteria.

Furthermore, even the most widely touted WSN projects remain limited by long-term reliability and power source options. Therefore, it is vital for the future of WSNs to develop wireless sensors that incorporate energy scavenging devices such as thermocouples, solar cells, or piezoelectric elements. Hurlebaus and Gaul (2006) have found this can greatly improve battery life and capabilities of the sensors. With respect to long-term reliability, Reinisch et al. (2007) indicates a potential challenge to wireless sensors is node visibility, i.e.: node 1 and 2 can see node 3, but not each other.

Some related works include a wireless solution to monitoring a tower in Trento, Italy and a noncontact and nondestructive solution to monitor a historic structure. Ceriotti et al. (2009) designed and implemented a WSN which utilizes accelerometers and deformation sensors to evaluate the static and dynamic state of the tower and “nodes to compensate for temperature effects.” This WSN was also set up with the capability to remotely adjust the system. This setup was later revised and an updated finite element model was incorporated with the collected data by Wu et al. (2010) with great success. On the other hand, the noncontact and nondestructive method of health monitoring using the measurement of dynamic results with a laser Doppler vibrometer (LDV) by Hossein and Tabrizi (2010) admittedly had difficulty with calibration on “highly inhomogeneous masonry.”

The purpose of this research is to develop and test a WSN for monitoring tilt in the walls of a historic structure under rehabilitation that is both non-destructive and cost effective. Sensors developed for the WSN will be capable of detecting the structural response to natural and man-made forces. The objectives of this field study are (1) develop a reliable WSN that caters to the special requirements for installation in historic structures, and (2) conduct a feasibility study of the WSN in the field.

The paper is structured as follows. Information on the historic structure, which includes a background on the building as well as rehabilitation plans, is preceded by a description of the WSN. Then, the implementation of the WSN for the historic structure is detailed, including mote placement,
installation, and the monitoring process. The paper is concluded with the presentation of the results and challenges.

**WIRELESS SENSOR NETWORK**

Wireless sensor networks are used to collect raw data from individual sensors and compile the information for analysis. They are advantageous due to the greater flexibility of a wire-free system and ease of installation; however, they are limited by the possibility of external conditions interfering with data transmission and power restrictions. The wireless sensors have the freedom to be placed at any location, which is only limited by transmission capacity of the transmitter and barriers such as metal and thick masonry or concrete walls. Another advantage of wireless sensors is that more can be easily added or removed once the initial WSN is in place. As interest grows in the field of wireless sensor technology, the sensors are becoming more widespread and the cost is decreasing. Also, the great decrease in installation costs often makes WSNs cost less than wired sensor networks.

Since battery life is a major limiting factor of WSNs, the search for more efficient methods of harvesting energy is underway. Suggested solutions include harvesting solar, thermal, or vibration energy, and/or creating batteries with greater efficiency. Due to the short term monitoring requirements of this specific application, the WSN used in this field study was designed for batteries only.

Three primary components make up the WSN: data collection, data accumulation, and data analysis (Figure 1).
For data collection, the wireless transmission module must be connected to a sensor module (comprising a complete mote), which are then attached to a structure. Many types and brands of motes exist for commercial and research use. This study tests Crossbow Mica2 series motes, a wireless sensor mote operating system that can easily be tailored for use with MTS310 sensor boards as displayed in Figure 2. A detailed description of Mica2 motes can be found in Reyer (2007). In this application, an Analog Devices ADXL202E accelerometer is used on the MTS310 sensor board.
Once the motes take the measurements, they use radio transmission to send the data to the base station. A basic star topology is used for communication between the motes and the base station (Figure 3). According to this configuration, all motes are set at the same priority level and are wirelessly connected to the base station. The priority level is used to set the hierarchy of the motes and indicates which motes are most important. By setting all motes to the same priority level, they are all given the same level of importance. Since the motes interact only with the base station and not one another, it is possible for individual motes to try to send data packets to the base station simultaneously. To ensure there is no data loss, the motes are programmed to continue to send their data until the base station confirms transmission. Once confirmation is received, the mote enters sleep mode and waits a user-defined amount of time before waking up and taking another measurement. The use of sleep mode conserves energy and helps extend battery life.

![Star topology](image)

Figure 3. Star topology (Samuels et al., 2010)

Through data acquisition, the other part of data accumulation, the base station creates a file on the computer that stores the mote number, date and time of measurement, and the raw acceleration values in the $x$ – and $y$ – coordinates.
Data analysis is the last aspect of the WSN. To complete the process, the file created in the data acquisition portion is imported into Matlab and plotted to determine the angle of tilt in the structure.

As previously mentioned, data from the motes provides raw data that must be calibrated to achieve meaningful results. For position 1 \([raw_y(+g)]\), orient the mote vertically so that the antenna is on the horizontal face of the top left corner. Position 2 \([raw_y(-g)]\) is where the mote is oriented vertically and the antenna is on the horizontal face of the bottom right hand corner (i.e., rotate the mote 180° from position 1). Orient the mote horizontally for position 3 \([raw_z(+g)]\) with the antenna on the top of the vertical right edge (i.e., rotate the mote 90° clockwise from position 1). Position 4 \([raw_z(-g)]\) requires the mote to be oriented horizontally with the antenna on the bottom left of the vertical edge (i.e., rotate the mote 90° counterclockwise from position 1). Note, all orientations are explained when facing the mote. A more detailed description can be found in Samuels et al. (2010). The acceleration values can be calculated using (Reyer, 2007)

\[
\delta_{x,y} = \frac{raw_{x,y}(+g) + raw_{x,y}(-g)}{2} \tag{1}
\]

\[
f_{x,y} = \frac{2[g]}{\left[raw_{x,y}(+g) - raw_{x,y}(-g)\right]} \tag{2}
\]

\[
a_{x,y} = (raw_{x,y} - \delta_{x,y}) \cdot f_{x,y} \tag{3}
\]

where \(\delta_{x,y}\) = calibration offset; \(raw_{x,y}(+g)\) = average raw data value for the mote in the positive \(g\) orientation in the \(x\) and \(y\) directions; \(raw_{x,y}(-g)\) = average raw data value for the mote in the
negative g orientation in the $x -$ and $y -$ directions; $f_{x,y}$ = calibration factor; $a_{x,y}$ = mote acceleration in the $x -$ and $y -$ directions, respectively (units of g). The angles of tilt can then be calculated using (Bryson et al., 2009; Analog Devices, 2000).

$$\theta_{x,y} = \sin^{-1}\left(\frac{a_{x,y}}{1g}\right),$$  \hspace{1cm} (4)

where $\theta_{x,y}$ = angle from the horizontal axis; $a_{x,y}$ = mote acceleration in the $x -$ and $y -$ directions, respectively (units of g).

**HISTORIC STRUCTURE**

St. Paul Lutheran, a historic masonry church with a timber-framed roof (Figures 4 & 5) in Serbin, Texas, is the focus of the field study. This structure, one of the Painted Churches of Texas, was completed in 1871 due to the efforts of Reverend Johan Kilian and a group of approximately 500 Lutheran Wends who emigrated from the region of Kotitz, Germany to escape religious oppression and for the right to speak their Wendish language (Geva, 2009; Lammert, 2010).

![Figure 4. Exterior view of St. Paul Lutheran](image_url)
As was typical of immigrants, the Wends brought parts of their culture with them to America. This is evidenced in the similarities between the Lutheran Church in Kotitz, Germany (Figure 6) and St. Paul Lutheran in Serbin, Texas (Figure 4). Although they were built approximately 200 years apart, Nielsen (1989) notes that both churches are designed with a “simple folk Gothic style”. In addition to a shared architectural style, the churches have a similar floor plan and construction plan. They each have a single nave rectangular plan with a bell tower and walls built of 0.762 m thick stone: sandstone in Germany and red sandstone in Texas. According to construction documents quoted in the St. Paul Lutheran Church pamphlet (2004), the church was to be “21.34 m long by 12.19 m wide, with walls 7.32 m high”. Four clear glass windows were placed on each side along the length of the church. The original exterior finish was coarse, while the interior had a fine finish. There was to be a tower and steeple, topped by a weathervane, which had a metal ball containing the history of Serbin, as written by Reverend Kilian. In comparison, the Kotitz Church was 17.68 m long by 11.58 m wide with a tower and steeple. A fine finish was used on both the interior and exterior, and the clear glass windows were located predominantly along the length of the structure.
While these structures have similarities on the exterior, the most striking resemblance is found in the interior, where the painted turquoise and blue interior, ornate chandeliers, pipe organ above the entrance, and multi-sided balcony of St. Paul mimic the Kotitz Church (Figure 7). In fact, the chandeliers at St. Paul’s are the original kerosene lamps that have been converted for electricity (St. Paul, 1980). Not only were the physical attributes of the interior similar, but the seating protocol of men sitting in the balcony and women and children staying on the ground floor was strictly followed (St. Paul, 2004).

According to Lammert (2010), “St. Paul’s is one of the oldest churches in America in continual use since its construction”. It is also said to have the highest pulpit in Texas because it is set on the balcony level, approximately 6.1 m off the ground floor.
REHABILITATION

Although the 0.762 m thick walls create a robust structure, the church is having settlement issues which are focused primarily towards the front entrance (west) of the church. These problems are most clearly manifested in the extensive cracking in the 1.27 cm thick plaster walls (Figure 8). The front exterior façade has cracking along almost the entire wall, which transferred through the 0.762 m thick stone walls and into the plaster on the interior. The load path of the structure is apparent by the extreme cracking in the pointed arches of the windows, which is worst near the front (west) wall and becomes less and less noticeable towards the back (east) wall (Figure 9). In fact, the stained glass windows nearest the front wall have deflected inwards approximately 7.62 to 10.16 cm, causing the glass to crack. In addition to the windows and plaster cracking, the differential settlements of the church have caused the ceiling to separate from the plaster walls at certain locations along the left (north) and right (south) walls (Figure...
10). The settlement in the ceiling is delineated in the extreme slope of the beams supporting the ceiling, which is easily visible to the naked eye (Figure 11).

Figure 8. Extensive cracking in the 1.27 cm thick plaster walls

Figure 9. Cracking in pointed arches of windows

Figure 10. Ceiling separated from wall
Once the construction workers start digging near the foundations, they discover the root of the settlement problems is a large amount of water trapped under the church’s foundations. To alleviate these problems, the foundations under the exterior walls of the church are underpinned, beam stiffeners are poured along the footings and the floor slab is replaced with a floating slab that is structurally detached from the wall foundations (Figure 12). Water barrier mats are installed at the foundation level to redirect water away from the church to ensure water does not become entrapped under the foundations in the future. After the church is stabilized, the exterior and interior are replastered as needed in four stages, starting with a rough plaster and moving to a smooth finish for the interior and a brushed finish for the exterior, both of which are painted a shade of cream (Figure 13). Since the front wall has the worst problems, the entire front exterior wall has to be replastered (Figure 14).
Figure 12. Foundation excavations and new footing (left, St. Paul Lutheran, 2010) and footing with beam stiffener (right, St. Paul Lutheran, 2010)

Figure 13. Four stages of plaster repair
During construction, the original stone floor is found under the concrete slab (Figure 15). The majority of the stone is able to be salvaged and although it is too uneven according to the Americans with Disabilities Act (ADA) standards to be reset on the interior of the church, it is planned to be reused at the entrance. To create a similar feel as the original floor, stone tiles are set on the new concrete slab (Figure 15).
MONITORING

At St. Paul Lutheran, each mote is mounted either on an angle bracket, which is attached to the wall on the balcony level with masonry screws and stabilized with a 3M removable poster strip or with a screw into the ceiling beams of the attic. The motes are oriented such that the local x-axis is perpendicular to the wall, while the local y-axis is parallel with the wall. As depicted in Figure 16, the motes are located predominantly on the front (west) end of the structure. This is the optimal placement because the motes are concentrated in the area that is experiencing the most issues. Note, Mote 8 is attached to the underside of a beam in the utility closed on the ground floor supporting the balcony, Motes 2, 7 and 13 are installed on the beams in the attic that comprise the ceiling above the balcony level, and the remaining motes are installed on the walls of the balcony level. Since this is a historic structure, consideration for the ideal mote placement along the height of the walls is also necessary. They were placed on the balcony level to minimize interference with the aesthetics of the church from the main floor. Because the majority of the foundation problems are concentrated at the entrance of the church, the motes are able to be installed in locations so that they are not visible from the main floor looking towards the altar.

Figure 16. Plan view of church with mote placement
The base station and desktop computer are set up along the wall on the balcony level. In the lab, the sensors were set to take measurements at 2 second time increments. Then, they were walked throughout the lab and taken outside of the lab to determine an approximate range at which the base station could still receive data from the mote. Once in the field, the base station was set up and the motes were all set in the approximate locations in which they were to be installed. Measurements were taken for several minutes to confirm that the base station was collecting readings from all of the motes. After confirming that data from all of the motes was reaching the base station, the motes were reprogrammed to take measurements at 15 minute increments and were installed. After all of the motes are in place, the WSN programs are started and data is saved on the computer. Internet access is not possible with the laptop card service provider in this field study due to a lack of coverage in such a remote location. All motes are removed once the structural foundation work is complete.

The WSN is installed three days prior to the start of construction and remains until all structural foundation work is finished and only tasks that would not impact the structure remain. The sensors used in this application have a sensitivity of approximately one degree. This degree of sensitivity was determined by collecting data with the mote sitting flat on a level surface and then rotating it 180 degrees from its original position. The difference between the average raw data value for the level position and the 180 degree position was divided by 180 degrees to reach one degree of sensitivity. The sensitivity was confirmed by following the same procedure, but with a 90 degree change of orientation. The motes are able to record movements throughout construction as a result of underpinning the foundations and digging under the church.

Motes 2 and 11 as shown in Figure 17 are chosen as examples. They display the results for a mote installed on an attic floor beam and a mote on the north wall near the stairs, respectively. The results for Motes 2 and 11 discussed in detail below. The results for other motes are summarized in Appendix A1-2.
For calibration, each mote is programmed to take static measurements at two second increments and placed in each of the four positions for 30 seconds per position. Raw data values from these orientations are then averaged to calculate the $\text{raw}_{x,y}(+g)$ and $\text{raw}_{x,y}(-g)$. Table 1 displays the raw data values as well as the $\delta_{x,y}$ and $f_{x,y}$ from Motes 2 and 11 as examples of this process.

Table 1: Calibration data for Motes 2 and 11

<table>
<thead>
<tr>
<th>Mote</th>
<th>raw$_y(+g)$</th>
<th>raw$_y(-g)$</th>
<th>raw$_x(+g)$</th>
<th>raw$_x(-g)$</th>
<th>$\delta_y$</th>
<th>$\delta_x$</th>
<th>$f_y$</th>
<th>$f_x$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>463.00</td>
<td>574.67</td>
<td>557.73</td>
<td>446.26</td>
<td>518.83</td>
<td>502.00</td>
<td>0.0179</td>
<td>0.0179</td>
</tr>
<tr>
<td>11</td>
<td>455.00</td>
<td>564.64</td>
<td>535.10</td>
<td>425.18</td>
<td>509.82</td>
<td>480.14</td>
<td>0.0182</td>
<td>0.0182</td>
</tr>
</tbody>
</table>

To verify the hypothesized correlation between construction activity and tilt in the walls, the plotted results are compared with the construction schedule. Table 2 displays the major activities of construction.
Table 2. Construction schedule

<table>
<thead>
<tr>
<th>Start Date</th>
<th>End Date</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/4/10</td>
<td>1/6/10</td>
<td>WSN installed before start of construction</td>
</tr>
<tr>
<td>1/7/10</td>
<td>1/12/10</td>
<td>Start excavation and place rebar (south side)</td>
</tr>
<tr>
<td>1/13/10</td>
<td>1/14/10</td>
<td>Start pouring around foundations; continue excavation and placing rebar (south side)</td>
</tr>
<tr>
<td>1/15/10</td>
<td>1/18/10</td>
<td>Rain delay</td>
</tr>
<tr>
<td>1/19/10</td>
<td>1/20/10</td>
<td>Continue excavation and pouring concrete around foundations; start pouring stiffener beams on top of footings (south side)</td>
</tr>
<tr>
<td>1/21/10</td>
<td>1/24/10</td>
<td>Clean up for wedding</td>
</tr>
<tr>
<td>1/25/10</td>
<td>1/25/10</td>
<td>Remove pews from church</td>
</tr>
<tr>
<td>1/26/10</td>
<td>1/26/10</td>
<td>Start excavation and place rebar (north side)</td>
</tr>
<tr>
<td>1/27/10</td>
<td>1/27/10</td>
<td>Start pouring concrete around foundations and stiffener beams on top of footings (north side)</td>
</tr>
<tr>
<td>1/28/10</td>
<td>2/8/10</td>
<td>Rain delay</td>
</tr>
<tr>
<td>2/9/10</td>
<td>2/15/10</td>
<td>Continue excavation, pouring concrete around foundations and stiffener beams on top of footings (north and east side)</td>
</tr>
<tr>
<td>2/16/10</td>
<td>2/17/10</td>
<td>Dig hole under church and prepare for more concrete footings; pour footings on east side, including beam under church</td>
</tr>
<tr>
<td>2/18/10</td>
<td>2/21/10</td>
<td>Continue pouring footings and prepare for stiffener beam on east side; north side completed; prep west side for excavations</td>
</tr>
<tr>
<td>2/22/10</td>
<td>2/22/10</td>
<td>Start excavation and place rebar (west side)</td>
</tr>
<tr>
<td>2/23/10</td>
<td>2/23/10</td>
<td>Snow delay</td>
</tr>
<tr>
<td>2/24/10</td>
<td>3/4/10</td>
<td>Start pouring around foundations; continue excavation and placing rebar (west side); start removing plaster from exterior walls</td>
</tr>
<tr>
<td>3/4/10</td>
<td>3/10/10</td>
<td>Foundation work complete; demo existing concrete slab, remove original stone floor underneath; Remove WSN on 3/10/10</td>
</tr>
</tbody>
</table>

Figures 18 and 19 illustrate x- and y-direction tilts of Mote 2 and 11, respectively. As was the case in a previous field study (Samuels et al. 2010), the y − direction indicated more movement than the x − direction throughout the monitoring process. The first few days (1/4/10 to 1/6/10) do not display any movement because construction does not start until 1/7/10. At the start of construction and as excavation and pouring concrete around the foundations commence (1/7/10 to 1/14/10) all motes trend out of alignment initially but then turned back towards the level position. This seems to indicate shifts in the walls during excavation which are recovered once the concrete is poured. From 1/15/10 to 1/18/10, construction is impeded due to a rain delay. During this time, each mote continues to level out. It is presumed that this occurs as the concrete gains strength and increases the stability of the structures foundations which are excavated. After the rain delay, the contractor has a couple of days (1/19/10 and
1/20/10) to continue work on the foundations before stopping work again to clean up for a wedding (1/21/10 to 1/24/10). The measurements are fairly stable during this cleaning period. The next construction activities are to continue excavation and pouring concrete around the foundations and stiffener beams on top of the footings (1/25/10 to 1/27/10). In this short time, little movement is detected by the motes. However, Mote 11 does become more level in the $y$ direction. Another rain delay disrupts construction from 1/28/10 to 2/8/10. Mote 11 has less movement in the second half of construction due to its location on the stone wall rather than on a wooden beam supporting the ceiling. This indicates that as the concrete is poured and cured, it stabilizes the structure so that Mote 11 sees less and less movement. The WSN is removed on 3/10/10. As can be seen, the trend line is level (0°) for all motes when the last measurements are recorded. Overall, Mote 2 detects more movement than Mote 11. This is because Mote 2 is installed on a wood beam in the attic whereas Mote 11 is attached to the stone wall. Obviously, stone is much more rigid than wood so more could be detected. All of the motes become less level during the rain delay. It should be noted, however, that this shift is fairly small (typically one degree or less). As construction begins again (2/9/10 to 2/22/10) and they continue excavation and pouring concrete around the foundations, Mote 2 becomes more level while Mote 11 remains relatively unchanged. Since it only lasts one day, the structure does not have any significant movement during the unheard of snow delay (2/23/10). After the snow delay, the only remaining foundation work is to finish excavation and pouring concrete around the foundations (2/24/10 to 3/3/10). At this point, the majority of the structure is secured, as evidenced by the relatively small amount of movement (if any) recorded by the motes, excluding Mote 2 in the $y$ direction. The foundation work is completed on 3/4/10 and as can be seen, the motes remain fairly stable after this point, except for Mote 2 in the $y$ direction. It is unclear as to what causes this shift while everything else remains unchanged, but as previously stated, this mote is on a wooden beam and is therefore more susceptible to movement. The fact that the motes (excluding Mote 2 in the $y$ direction) showed no significant movement from the end of the foundation work to the end of the measurement period (3/4/10 to 3/10/10) confirms the
analysis of the structural engineer that the floor slab is detached from the structural system of the walls. This is proven because during this time, the existing concrete slab is demolished and the original stone floor underneath is removed.

Figure 18. Tilt of Mote 2 in x-direction (top) and y-direction (bottom)
Figure 19. Tilt of Mote 11 in x-direction (top) and y-direction (bottom)

For an additional comparison, the temperature at the church is plotted each day at 20 minute increments (Figure 20). The local temperature data were obtained from the WeatherUnderground.com. The figure displays the wide range of temperatures for which the sensors can be implemented.
Maintaining power and minimizing data loss is the primary limiting factor of the WSN. To address these challenges, the computer and base station are connected to an uninterruptable power supply. For this application, it is determined that batteries are the best power source for the wireless motes. Lab tests are conducted to identify the ideal type of battery and time increment for measurements. In these tests, motes are programmed for three different time increments (2 seconds, 15 minute, and 1 hour). Voltages of the new batteries are measured before installation and take measurements for three days, when the total voltage is measured again. Duracell Alkaline AA, Panasonic Industrial Alkaline AA and Energizer Lithium AA are each tested using each of the time increments (Table 3). The results concluded that Energizer Lithium AA batteries perform best when the motes took readings at 15 minute increments. Using this configuration, the motes require a change of batteries once a month. In a previous field study of a wood-framed historic church undergoing foundation leveling (Samuels et al., 2010), major gaps in data transmission were experienced. As can be seen in Figures 18 and 19, changing of batteries once a month greatly improved the consistency of data transmission.

Figure 20. Temperature at St. Paul Lutheran during monitoring
Table 3: Battery life investigation

<table>
<thead>
<tr>
<th>Time Increment</th>
<th>Battery Type</th>
<th>Elapsed Time (days)</th>
<th>Δ Voltage</th>
<th>Voltage drop/day</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 s</td>
<td>Duracell Alkaline</td>
<td>3.056</td>
<td>0.329</td>
<td>0.108</td>
</tr>
<tr>
<td>2 s</td>
<td>Energizer Lithium</td>
<td>7.860</td>
<td>0.225</td>
<td>0.029</td>
</tr>
<tr>
<td>2 s</td>
<td>Panasonic High Power Alkaline</td>
<td>3.213</td>
<td>0.315</td>
<td>0.098</td>
</tr>
<tr>
<td>15 min</td>
<td>Duracell Alkaline</td>
<td>3.056</td>
<td>0.307</td>
<td>0.100</td>
</tr>
<tr>
<td>15 min</td>
<td>Energizer Lithium</td>
<td>7.860</td>
<td>0.237</td>
<td>0.030</td>
</tr>
<tr>
<td>15 min</td>
<td>Panasonic High Power Alkaline</td>
<td>3.188</td>
<td>0.168</td>
<td>0.053</td>
</tr>
<tr>
<td>1 hr</td>
<td>Duracell Alkaline</td>
<td>3.056</td>
<td>0.317</td>
<td>0.104</td>
</tr>
<tr>
<td>1 hr</td>
<td>Energizer Lithium</td>
<td>7.860</td>
<td>0.199</td>
<td>0.025</td>
</tr>
<tr>
<td>1 hr</td>
<td>Panasonic High Power Alkaline</td>
<td>3.188</td>
<td>0.170</td>
<td>0.053</td>
</tr>
</tbody>
</table>

CONCLUSIONS

Through this research, a wireless sensor network was developed and implemented in the field over the course of rehabilitation. Analysis of the data indicates that the motes detected long-term tendencies in the tilt of the walls in spite of their low sensitivity. It is recommended that in future work, this analytical approach should incorporate structural analysis software to determine safe limits for the historic fabric of the structure. Once these thresholds are set, they should be implemented in the WSN output and formatted for use in real-time analysis to warn the structure’s supervisor if the tilt exceeds the specified limits. Also, it is suggested that motes with higher sensitivity be used for future structural applications, but it should be noted that this was simply a field test to establish whether or not the WSN developed could detect tilt shifts in the walls due to rehabilitation processes. As seen in the results, this research improved upon previous cases by decreasing data and power loss, and therefore, can serve as a spring board upon which future research can expand.

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References


