Integration of a prototype wireless communication system with micro-electromechanical temperature and humidity sensor for concrete pavement health monitoring

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Abstract
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Keywords
CNDE, Electrical and Computer Engineering, pavement, structural health monitoring, wireless, sensor, temperature, humidity, concrete, MEMS

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Integration of a prototype wireless communication system with micro-electromechanical temperature and humidity sensor for concrete pavement health monitoring

Shuo Yang1, Keyan Shen2, Halil Ceylan1*, Sunghwan Kim1, Daji Qiao2 and Kasthurirangan Gopalakrishnan1

Abstract: In recent years, structural health monitoring and management (SHMM) has become a popular approach and is considered essential for achieving well-performing, long-lasting, sustainable transportation infrastructure systems. Key requirements in ideal SHMM of road infrastructure include long-term, continuous, and real-time monitoring of pavement response and performance under various pavement geometry-materials-loading configurations and environmental conditions. With advancements in wireless technologies, integration of wireless communications into sensing device is considered an alternate and superior solution to existing time- and labor-intensive wired sensing systems in meeting the requirements of an ideal SHMM. This study explored the development and integration of a wireless communications sub-system into a commercial off-the-shelf micro-electromechanical sensor-based

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PUBLIC INTEREST STATEMENT

Frequent monitoring of health of any system (human or man-made) is important to ensure that it is functioning optimally and to identify any corrective measures. Concrete pavement systems are no different. Traditionally, the structural health of such systems have been monitored using embedded sensors connected to data acquisition systems through long wires. However, the use of wired sensors can be very time-consuming and costly, especially if a large number of sensors have to be installed. Recent advancements in wireless technologies and development of miniature (micro-scale) sensing devices have the potential to enable the promise of smart pavement health monitoring systems. This paper describes the development and field performance of a wireless micro-electromechanical sensor system (MEMS) for monitoring concrete pavement temperature and relative humidity.
concrete pavement monitoring system. A success-rate test was performed after the wireless transmission system was buried in the concrete slab, and the test results indicated that the system was able to provide reliable communications at a distance of more than 46 m (150 feet). This will be a useful feature for highway engineers performing routine pavement scans from the pavement shoulder without the need for traffic control or road closure.

Subjects: Engineering & Technology; Concrete & Cement; Pavement Engineering; Transportation Engineering

Keywords: pavement; structural health monitoring; wireless; sensor; temperature; humidity; concrete; MEMS

1. Introduction
Like many advanced technologies, wireless sensor technologies were initially developed and deployed for military and industrial purposes (SILICON LABS, 2015). In recent years, these kinds of technologies are extensively applied in civil engineering infrastructure to measure the changes in material and geometric properties for serviceability assessment, which is referred to as structural health monitoring (SHM). Over past decades, SHM has been widely used in civil engineering infrastructure to monitor structural integrity failures such as cracks, structural deterioration, and steel corrosion. An early warning could avoid unnecessary costs to the maintenance programs. Moreover, continuously measured data can contribute to improved modeling and analytics resulting in prolonged system service life and reduced life cycle costs (Barroca et al., 2013; Buenfeld, Davis, Karmini, & Gilbertson, 2008; McCarter & Vennesland, 2004). Wired sensor systems are widely used in traditional SHM to detect structural damage (Lynch, 2002). However, the use of wired sensors can be very time-consuming and costly if a large number of sensors have to be installed to improve quality of measured data in SHM (Cepero, 2013; Cho et al., 2008; Lynch, Sundararajan, Law, Kiremidjian, & Carryer, 2003). Furthermore, in cases where wires are buried in concrete, wires may be corroded or damaged (Cepero, 2013; Cho et al., 2008; Lynch et al., 2003). Due to these drawbacks, the use of wireless technologies is considered to be a promising substitute to provide better functionality at a lower price especially when a higher spatial density of sensors is desired (Kim et al., 2007). In addition, micro-electromechanical sensors and systems (MEMS) technology has been investigated for SHM since MEMS make it possible for systems of all kinds to be smaller, faster, more energy-efficient, and less expensive (Ceylan et al., 2011, 2013).

Numerous studies have been conducted to apply wireless sensor technologies in bridge system SHM (Maser, Egri, Lichtenstein, & Chase, 1996; Loh, Zimmerman, & Lynch, 2007; Lynch, 2007; Lynch & Loh, 2006). However, only few recent studies have investigated these technologies in pavement SHM applications. For instance, Lajnef, Chatti, Chakrabarty, Rhimi, and Sarkar (2013) focused on development of a wireless strain sensing system for asphalt pavement SHM to detect fatigue damage. The sensor system developed in this study contained a low-power consumption wireless integrated circuit sensor interfaced with a piezoelectric transducer. This piezoelectric ceramic transducer was designed with an array of ultra-low power floating gate (FG) computational circuits and it could generate power to supply FG analog processor in the sensor under stress. Each sensor node could store the data and then periodically transmit them to radio frequency (RF) reader mounted on a moving vehicle (Lajnef, Rhimi, Chatti, Mhamdi, & Faridazar, 2011).

The objective of this current study is to investigate the feasibility of developing wireless-based MEMS for concrete pavement SHM. A wireless network system was integrated with an off-the-shelf MEMS sensor, originally designed and configured for wired data acquisition. The field performance of commercial wired MEMS sensors was evaluated in a newly constructed concrete pavement under actual traffic load and weather conditions to identify the system requirements for development of the wireless MEMS sensor system. A preliminary design of the prototype wireless system with robust packaging was developed to improve the survivability of MEMS sensors. The wireless system utilized
XBee-PRO modules interfaced with Arduino boards (http://pdf1.alldatasheet.com/datasheet-pdf/view/530828/TI/TPL5000.html) to build the transmission system based on ZigBee protocol. Detailed discussions and findings pertaining to the development of wireless-based MEMS are discussed.

2. Evaluation of commercial off-the-shelf wired MEMS sensors

2.1. Sensor description

Temperature and moisture content are significant factors in the hydration process between cementitious materials and water, which in turn influence early-age concrete properties (Norris, Saafi, & Romine, 2008; Saafi & Romine, 2005). Anomalies in the hydration process may result in insufficient strength and durability since the development of early concrete strength mainly depends on the moisture diffusion and hydration temperature (Choi & Won, 2008; Every, Faridazar, & Deyhim, 2009; Ye, Zollinger, Choi, & Won, 2006). Furthermore, concrete pavement can be subjected to deformation due to different temperature and moisture gradients throughout the concrete slab, commonly referred to as curling (temperature) and warping (moisture/humidity) behaviors. This, when combined with heavy traffic loading, could lead to cracking of slabs. Considering the significant impact of temperature and moisture conditions on the overall concrete pavement response and performance (Ruiz, Rasmussen, Chang, Dick, & Nelson, 2005), these two properties were selected for investigation in this study. Continuous wireless monitoring and communication of temperature and moisture changes within in-service concrete pavements can provide an early warning and alert the highway engineers/agencies regarding their potential for structural integrity failure. This can enable the selection of appropriate pavement distress mitigation and preventive strategies resulting in sustainable and durable pavement systems.

The Sensirion SHT71 digital humidity sensor, classified as a commercial off-the-shelf MEMS device that can simultaneously measure relative humidity (RH) as well as temperature, was evaluated in this study. Note that moisture content measured inside concrete is typically expressed as RH which refers to the ratio of moisture content of air compared to saturated moisture level at the same temperature and pressure (Ye et al., 2006).

The commercial MEMS digital humidity sensor integrates sensor elements coupled with signal processing circuitry on a silicon chip by MEMS technology to provide a fully calibrated digital output. A unique capacitive sensor element consisting of paired conductors is built out of the capacitor of MEMS sensor to capture humidity while another band-gap sensor measures temperature. These conductors are separated by a polymer dielectric that can absorb or release water proportional to the relative environmental humidity, and thus can change the capacitance of the capacitor (Sensirion Inc., 2014, http://www.sensirion.com/en/technology/humidity/). An electronic circuit calculates RH by measuring the capacitance difference. Additionally, the capacitance for the chip of this MEMS sensor is formed by a “micro-machined” finger electrode system with different protective and polymer cover layers, which can simultaneously protect the sensor from interference as well. However, in order to continuously monitor and store measurement data, MEMS sensors have to be connected with a data reader of evaluation kit EK-H4 (see Figure 1) and a computer which require power (battery) supply all the time.

2.2. Field instrumentation and findings

A set of four wired commercial MEMS RH/temperature (RH/T) sensors were instrumented in a newly constructed jointed plain concrete pavement (JPCP) in a US-30 highway section near Ames, Iowa, USA. The instrumented JPCP, constructed at 8:00 am on 24 May 2013, consists of 254 mm (10 inch) thick concrete slab with approximately 6 m (20 feet) transverse joints spacing. The passing lane and travel lane widths for this JPCP are 3.7 m (12 feet) and 4.3 m (14 feet), respectively. A 152 mm (6 inch) thick Hot-Mix Asphalt (HMA) shoulder was constructed approximately 28 days after the paving of concrete. A set of wireless temperature sensors and longitudinal strain gauges were installed in the same section along with the commercial MEMS RH/T sensors for another series of investigations, not part of this study.
Before the paving of concrete took place, the RH/T sensors were tied on to short wood sticks installed on top of the base course. As seen in Figure 2, all the cables/wires from the sensors were tied together and then placed in a polyvinyl chloride (PVC) pipe buried underground to protect them from damage during concrete paving operations. The cables in the PVC pipe were connected to a data acquisition system (DAS) equipment (laptop, data logger, evaluation kit, and batteries) in a plastic shield box placed near the drainage ditch away from the HMA shoulder (see Figure 3). The installation of these wired sensors required great care, was time consuming and labor-intensive.

Figure 4 illustrates measured temperature and RH profiles captured by wired MEMS RH/T sensors one month after concrete paving. This figure shows measurements from MEMS RH/T sensor No. 3 (installed at 51 mm (2 inch) below pavement surface and 711 mm (28 inch) away from shoulder) and MEMS RH/T sensor No. 4 (installed at 2.5 mm (0.1 inch) below pavement surface and 203 mm (8 inch) away from shoulder). Among the four sensors installed before paving, two sensors (No. 3 and 4) remained functional in measuring temperature inside concrete while one sensor (No. 4) measured only RH of concrete.
The other two sensors, No. 1 and 2 (installed at 216 mm (8.5 inch) and 140 mm (5.5 inch) below pavement surface and 711 mm (28 inch) away from shoulder), malfunctioned several hours after concrete paving operations. This could probably be attributed to damages incurred to the wires/cables from concrete paver and vibrator operations. The sensor itself could also have been damaged.
because of the high alkali environment prevailing during concrete hydration. Data could not be acquired from 26 May to 28 May 2013 since the battery (power supply) for the DAS was not recharged. These practical constraints and limitations of wired sensor systems with respect to continuous monitoring and storage of measured data highlight the need for a self-powered, wireless sensor system.

### 2.3. Lessons learned from field evaluation

The on-site experiences from US-30 highway sensor installation and monitoring and the identified limitations of wired sensor systems proved to be resources in identifying the system requirements in the development of wireless MEMS sensor systems. These limitations include time-consuming and labor-intensive installation process, poor sensor survivability caused by cable damage, and complicated sensor packaging required to protect sensor from high alkali environment during concrete hydration.

Critical factors to be considered in wireless MEMS sensor systems include hardware architecture, packaging, embedded software, wireless signal strength, and low-power consumption under on-site conditions. Considering these critical factors, a preliminary wireless system with a robust packaging for MEMS sensors was developed.

### 3. Development of a prototype wireless communication system

#### 3.1. Overview

The wireless communications system presented in this study is a preliminary design mainly focusing on the wireless transmission function. In this study, an Institute of Electrical and Electronics Engineers (IEEE) standard-based wireless system was utilized because of both its low price and its low power consumption. A MEMS digital humidity sensor was used as sensing unit; this pin-based sensor had no packaging for its sensing element so an additional robust packaging system was also required. The wireless system could be divided into two parts: wireless transmission end and wireless receiving end. The wireless transmission end is used to transfer data from MEMS sensors into wireless transmission devices. The wireless receiving end connected with computer is used to download data without the need for a wire. Microcontrollers and XBee-PRO modules are required for the transmission and receiving ends to communicate with each other.

#### 3.2. Wireless network protocol

Wireless network protocols are used to define or standardize the rules and conventions for communication between devices (Lee, Su, & Shen, 2007). The wireless system implemented in this design was ZigBee, used to construct a decentralized self-healing wireless mesh network. In this mesh network, nodes can find a new route when an original route fails (Texas Instruments, 2013). ZigBee uses an IEEE 802.15.4-based protocol; in addition to ZigBee, there are also other possibilities, including Bluetooth, Wi-Fi, cellular, etc. Table 1 gives a comparison between different wireless technologies by evaluating their total scores derived from weighted scores considering various aspects such as data rate, range, and energy consumption. In this table, the weighted score of each aspect is calculated by multiplying its weight by the score of each specific wireless technology; a higher total score represents a better wireless technology for this application. Based on this table, it can be seen that ZigBee is more energy-efficient, cost-effective, and easier to work with than the other technologies.

#### 3.3. Microcontrollers

The Arduino board is a single-board microcontroller employing an Atmel AVR® 8-bit or 32-bit microcontroller that can be wirelessly programmed by a device utilizing the ZigBee protocol (Atmel, 2014, [http://www.atmel.com/products/microcontrollers/avr/](http://www.atmel.com/products/microcontrollers/avr/)). In the present study, Arduino Uno and Arduino Mega 2560, respectively, shown in Figure 5, were used for wireless transmitter and receiver.
The Arduino Uno is a microcontroller using an ATmega328 processor with 32 KB of flash memory, 2 KB of static random-access memory (SRAM), and 1 KB of electrically erasable programmable read-only memory (EEPROM). The board has 14 digital input/output pins, 6 analog inputs, a 5-volt linear regulator, a 16 MHz ceramic resonator, a USB connection, a power jack, an In-Circuit Serial Programming header, and a reset button. The Arduino Mega 2560 is similar to the Arduino Uno but it has an ATmega2560 processor with 54 digital input/output pins, 16 analog inputs, 4 hardware serial ports (UARTs), and a 16 MHz crystal oscillator. The Arduino Mega 2560 is compatible with most shields.

Table 1. Comparison of wireless technologies (Al-Khatib et al., 2009)

<table>
<thead>
<tr>
<th>Aspects</th>
<th>Score (0–10, with 0 being the worst and 10 being the best)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Factors</td>
<td>Weight</td>
</tr>
<tr>
<td>Multi-node network support</td>
<td>100</td>
</tr>
<tr>
<td>Throughput</td>
<td>60</td>
</tr>
<tr>
<td>Data rate</td>
<td>60</td>
</tr>
<tr>
<td>Range</td>
<td>50</td>
</tr>
<tr>
<td>Ease of implementation</td>
<td>50</td>
</tr>
<tr>
<td>Power consumption</td>
<td>–80</td>
</tr>
<tr>
<td>Cost</td>
<td>–100</td>
</tr>
<tr>
<td>Total score</td>
<td>460</td>
</tr>
</tbody>
</table>

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designed for the Arduino Duemilanove or Diecimila and it has 256 KB of flash memory, 8 KB of SRAM, and 4 KB of EEPROM for storing code and data. These two microcontrollers were selected because of their high reliability and low cost. Furthermore, Arduino 1.0.4 (open-source software) can be used for program coding such as setting up a time interval and changing the format of exported data, to control both the Arduino Uno and the Arduino Mega 2560.

3.4. XBee-PRO modules
XBee-PRO RF module (series 1) as shown in Figure 6 is a wireless device, which can offer low-cost wireless connectivity in ZigBee (Digi, https://www.digi.com/technology/RF-articles/wireless-zigbee) mesh networks. It is reliable in point-to-point, multipoint wireless transmission and it is designed to meet the IEEE 802.15.4 standard. Furthermore, XBee-PRO module also has an easy setup process and the software used to program is called X-CTU, which adjusts its frequency, signal strength, energy consumption, and so on. Additionally, an XBee Explorer Regulated board can be used to help it regulate the voltage input.

3.5. Wireless transmission
The wireless transmission end, as shown in Figure 7, consists of a MEMS sensor (SHT71 digital humidity and temperature sensor), an XBee-PRO module, an XBee Explorer Regulated, an Arduino Uno microcontroller, and 12 × 1.5 V AA batteries. Among these devices, XBee Explorer Regulated is a board that can be pinned on XBee-PRO to help it regulate the voltage input. In the wireless transmission end, both the SHT71 sensor and XBee-PRO with XBee Explorer Regulated were pinned on the digital port and power port on Arduino Uno board. Meanwhile, 12 1.5 V AA batteries were placed in
a plastic holder connected with the microcontroller to power the entire wireless transmission end through the voltage output pin on the board. Furthermore, because the entire wireless transmission end will be buried in concrete, a robust packaging framework is needed for the wireless transmission system which will be discussed later.

3.6. Wireless reception

The wireless receiving end, as shown in Figure 8, consists of an XBee-PRO module, an XBee Explorer Regulated, and an Arduino Mega 2560 microcontroller. The XBee Explorer Regulated here plays the same role as it was used in the wireless transmission end. However, there were no batteries on the Arduino Mega 2560 because it was powered by computer through a USB cable. The XBee-PRO on the Arduino Mega 2560 was paired with the other XBee-PRO on the Arduino Uno in the wireless transmission end to receive the transmitted data. After that, the data will be stored in a data-storage module with 4096 bytes non-volatile memory on the Arduino Mega 2560.

3.7. Packaging

Robust packaging is required to protect both the sensor and wireless transmission devices like the XBee-PRO module and the microcontroller to ensure that they work properly inside the concrete. The packaging functions include protecting the wireless transmitter during sensor installation and pavement construction processes, protecting the sensor from alkali-cement hydration reaction, and protecting the wireless transmitter under harsh climate and traffic conditions.
Two kinds of in-house packaging were designed to protect the sensor, microcontroller and XBee-PRO module, respectively. For the MEMS sensor, a piece of adhesive tape, a protection filter cap, and steel wool were used to make the protective package to prevent direct contact between the raw sensor and fresh concrete. In this packaging, a filter cap was placed on the top of the MEMS sensor using adhesive tape. Steel wool was used to attach the sensor (Figure 9). As for the microcontroller and XBee-PRO module, a small box with the bottom open, consisting of 12 mm thick wood board and a wood board nailed with a 180 mm long sharp-edged wood stick, was prepared. A hole was drilled on the board nailed with the stick to allow the cable from the sensor to go through to connect the Arduino Uno microcontroller. The size of the box was 160 mm × 105 mm × 88 mm (6.3” × 4.1” × 3.5”) which was sufficient to place the entire wireless transmission system, as shown in Figure 10. Silicon glue and adhesive tape were used as well to seal the small gap in the box.

4. Evaluation of developed prototype wireless communication system

4.1. Working principle

The data-exchange principle of this wireless system is based on the ZigBee protocol. This system requires no external cables. When it is turned on, the MEMS sensor will sense temperature and RH and transfer that data to the XBee-PRO through the Arduino Uno microcontroller. Then the XBee-PRO, using the wireless transmitter, will transmit data to the paired XBee-PRO at the wireless receiver through an antenna; this data will be stored in the Arduino Mega 2560, so the wireless receiver and a computer must be placed nearby because only the Arduino Mega 2560 microcontroller is used to store data in this wireless system. The data can finally be downloaded to the computer through software called “CoolTerm,” (http://download.cnet.com/CoolTerm/3000-2383_4-10915882.html#ixzz2ueTEGqCd) a simple freeware
serial port terminal application without terminal emulation that supports data exchange with hardware connected through serial ports (Sparkfun Electronics, 2014, https://learn.sparkfun.com/tutorials/terminal-basics/coolterm-windows-mac-linux). Temperature, relative humidity, and dew point are the data elements exported from the system.

4.2. Comparison between wired and wireless MEMS system

Figure 11 provides an overall system-level comparison between wired MEMS system and wireless MEMS system developed. In the wired MEMS system, the sensor must be connected to the data reader and the computer through cables to continuously monitor concrete properties and the data, so both the data reader and the computer require an electrical power supply. However, the implemented wireless system requires no external cables and can thereby save installation time and reduce the risk of sensor malfunction.

4.3. Evaluation of wireless communication capacity

To test the reliability and survivability of the wireless communication system inside the concrete, both wireless transmitter and receiver were embedded in concrete as shown in Figure 12 to conduct a success-rate test. Success rate refers to the success rate of data transmitted from the transmitter in successfully reaching the receiver. The higher this rate, the more reliable the system will be.

The success-rate test was conducted for wireless MEMS system inside concrete buried underground by increasing horizontal and vertical distances between wireless transmission and receiving ends (see Figure 13). Figure 14 illustrates success rates (in transmitting concrete pavement temperature

Figure 11. Comparison between wired MEMS system and implemented wireless-based MEMS system.

Figure 12. Wireless MEMS system inside concrete.
Figure 13. Success-rate test: (a) wireless MEMS system inside concrete buried underground; (b) measuring horizontal distance; and (c) four positions to measure vertical distance.

![Image of a wireless MEMS system inside concrete and measuring distances]

Figure 14. Success-rate test results.

![Graph showing success rates at different horizontal distances for ground, crouch, stand, and above head positions]
and RH measurements) at different working distances which tend to indicate that the implemented wireless MEMS system can maintain high success rate (greater than 92%) at a horizontal distance of over 46 m (150 feet). Also, the success rate tends to increase as the vertical distance decreases, especially at higher horizontal distances.

The temperature and RH measurements acquired by the wireless sensor system during the success-rate test are presented in Figures 15 and 16. As mentioned before, the implemented wireless communication system was able to transmit temperature and RH measurement when the receiver was positioned approximately 46 m away from transmission end with an almost 100% success rate.

5. Summary, findings, and recommendations
The objective of this study was to investigate the feasibility of implementing wireless-based MEMS for concrete-pavement structural-health monitoring. The system requirements for the wireless MEMS system were derived from field experience using a US-Highway-30 wired MEMS system. In this design, a wireless communication system was integrated with off-the-shelf MEMS sensors originally designed to be wired. The wireless MEMS system developed was capable of providing reliable temperature and RH measurement data over a distance of more than 150 feet from the receiver when embedded in concrete. However, the entire system was still consuming energy from a currently limited energy source. It could work for just a few days at a reasonable data-sampling rate using 12 1.5 AA batteries. The lifetime of these batteries could easily be diminished by harsh environmental factors like high temperatures occurring during concrete hydration; extremes of both temperature and humidity can reduce the lifetime and capacity of such batteries. One attractive, but not necessarily easy solution to this whole issue, is to develop a self-powered system that can utilize electromagnetic wave, wind, solar, thermo-electricity, and physical vibration to power sensor operation (Yildiz, 2009). Among these options,
physical vibration could be an ideal energy source for pavement health monitoring applications since it can be obtained from moving vehicles on pavements. Furthermore, future research should focus on increasing memory capacity and making the whole system smaller.

Some recommendations to resolve the aforementioned issues are:

• A power management circuit called Texas Instruments (2014, http://pdf1.alldatasheet.com/datasheet-pdf/view/530828/TT/TPL5000.html) Debuts TPL5000 power timer can be used to control power output of battery; this can possibly extend the current working time to as much as several years under ideal conditions.

• A micro-SD card or QuadRom Shield can be added to the microcontroller to tremendously increase its memory capacity.

• A smaller microcontroller called Arduino Fio with XBee plug can be used to replace the original microcontroller to reduce the overall system size.

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