A Feasibility Study on Embedded Micro-Electromechanical Sensors and Systems (MEMS) for Monitoring Highway Structures

National Concrete Pavement Technology Center

Tech Center

Final Report
June 2011

IOWA STATE UNIVERSITY
Institute for Transportation

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16. Abstract

Micro-electromechanical systems (MEMS) provide vast improvements over existing sensing methods in the context of structural health monitoring (SHM) of highway infrastructure systems, including improved system reliability, improved longevity and enhanced system performance, improved safety against natural hazards and vibrations, and a reduction in life cycle cost in both operating and maintaining the infrastructure. Advancements in MEMS technology and wireless sensor networks provide opportunities for long-term, continuous, real-time structural health monitoring of pavements and bridges at low cost within the context of sustainable infrastructure systems.

The primary objective of this research was to investigate the use of MEMS in highway structures for health monitoring purposes. This study focused on investigating the use of MEMS and their potential applications in concrete through a comprehensive literature review, a vendor survey, and a laboratory study, as well as a small-scale field study. Based on the comprehensive literature review and vendor survey, the latest information available on off-the-shelf MEMS devices, as well as research prototypes, for bridge, pavement, and traffic applications were synthesized.

A commercially-available wireless concrete monitoring system based on radio-frequency identification (RFID) technology and off-the-shelf temperature and humidity sensors were tested under controlled laboratory and field conditions. The test results validated the ability of the RFID wireless concrete monitoring system in accurately measuring the temperature both inside the laboratory and in the field under severe weather conditions.

In consultation with the project technical advisory committee (TAC), the most relevant MEMS-based transportation infrastructure research applications to explore in the future were also highlighted and summarized.

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EXECUTIVE SUMMARY

The development of novel "smart" structures by embedding sensing capabilities directly into the construction material during the manufacturing and deployment process has attracted significant attention in the context of autonomous structural health monitoring (SHM). Advancements in micro-electromechanical sensors and systems (MEMS) technology and wireless sensor networks provide opportunities for long-term, continuous, real-time SHM of pavements and bridges at low cost within the context of sustainable infrastructure systems.

The primary objective of this research was to investigate the use of MEMS in highway pavement infrastructure for SHM purposes. This study focused on investigating the use of MEMS and their potential applications in portland cement concrete (PCC) through a comprehensive literature review, a vendor survey, and a laboratory study, as well as a small-scale field study. These are the highlights of the study:

- A state-of-the-art survey on MEMS for transportation infrastructure monitoring applications was conducted. Based on a comprehensive literature review, the latest information available on off-the-shelf MEMS devices, as well as research prototypes, for bridge, pavement, and traffic applications were synthesized.

- The WAKE, Inc. radio-frequency identification (RFID) wireless HardTrack Concrete Monitoring System, the Sensirion Inc. USA Digital Humidity Sensor, and the Maxim Integrated Products Thermochron iButtons were evaluated under controlled laboratory and field conditions. The test results validated the ability of the RFID wireless concrete monitoring system in accurately measuring the temperature both inside the laboratory and in the field under severe weather conditions.

- In consultation with the project technical advisory committee (TAC), the most relevant MEMS-based transportation infrastructure research applications to explore in the future phases of this research were highlighted and summarized. These include development of a pavement strain monitoring system, an overweight/heavy vehicle pre-alert and detection system, a critical stop sign tracking/monitoring system, a traffic flow detection and wrong-way vehicle control and warning system, and a black ice detection and warning system.

INTRODUCTION

Background

Micro-electromechanical sensors and systems (MEMS) claim to be the smallest functional machines that are currently engineered by humans (Korvink and Paul 2006). These micro machines began their development as early as the 1970s, but, since 1995, there has been significant progress given a variety of new materials and bulk micromachining, which has led to new applications for MEMS (Gaura and Newman 2006).

MEMS have been developed in many areas including the medical and automotive industries. This technology is beginning to be introduced into the civil and construction engineering industry. There are a number of research projects exploring ways to apply the MEMS technology to help enhance structural health monitoring (SHM) practices in civil engineering.

By incorporating MEMS sensor technology into SHM of highway infrastructure, there are potential benefits that include improved system reliability, improved longevity and enhanced system performance, improved safety against natural hazards and vibrations, and a reduction in life cycle cost in both operating and maintaining the infrastructure (Attoh-Okine 2003).

First developed in the 1970s and then commercialized in the 1990s, MEMS make it possible for systems of all kinds to be smaller, faster, more energy-efficient, and less expensive. In a typical MEMS configuration, integrated circuits (ICs) provide the “thinking” part of the system, while MEMS complement this intelligence with active perception and control functions (AllAboutMEMS 2002).

The functions of sensing and actuating with computation and communication are merged in MEMS technology to locally control physical parameters at the micro scale. A number of duplicate devices joined together can cause effects at much greater scales. Figure 1 shows the main components of MEMS (Attoh-Okine 2003).

Other advantages of MEMS-based systems include low cost through mass production, in addition to reducing size and mass. Because MEMS are produced with the same processes as semiconductors, large-scale systems integration is possible on a single silicon chip.

MEMS devices can be classified into three broad categories (Maluf 2000): sensors, actuators, and passive structures. Transducers that convert mechanical, thermal, or other forms of energy into electrical energy are considered sensors; whereas, actuators do the exact opposite. Devices in which no transducing occurs are passive structures. Some intrinsic properties, such as piezoresistivity, piezoelectricity, or thermoelectricity of the component, determine the actuation or sensing ability of MEMS (Attoh-Okine 2003).

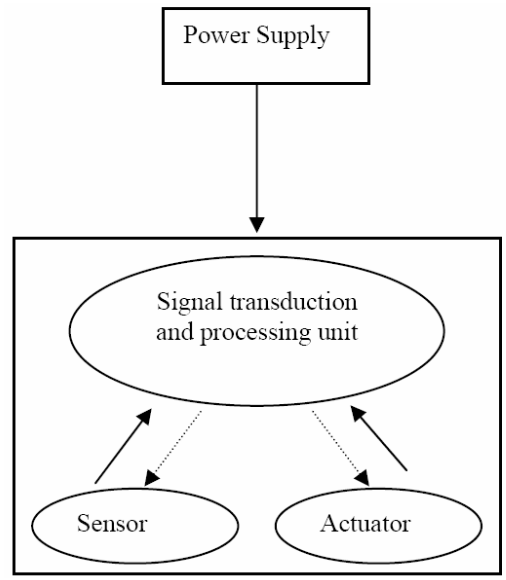


Figure 1. Main components of MEMS (Attoh-Okine 2003)

MEMS technology could potentially help pavement monitoring by obtaining in situ condition data. This data would tell engineers when and where pavement deterioration is occurring before the distress is noticeable to the traveling public.

There was significant concern about the safety of America's bridge network in the late 1960s after the collapse of the Silver Bridge on December 15, 1967. The Silver Bridge spanned the Ohio River connecting West Virginia and Ohio. There were 46 fatalities and a number of injuries. Following this event, bridge inspection and replacement programs were implemented. Most bridges are currently monitored by periodic visual safety inspections.

MEMS could help bridge inspection by providing data from within the bridge structure, and MEMS sensors have the capabilities to measure a variety of different properties useful for bridge inspection, such as pH, corrosion, strain, accelerometers, pressure sensors, and flow. MEMS incorporated into a wireless sensor network would potentially allow bridge inspectors to retrieve real-time bridge data.

The following are some areas of highway infrastructure condition monitoring where the application of MEMS technology is actively being researched or is identified for future research:

- Micrometer strain gauge for geotechnical testing (triaxial testing) and asphalt material testing (resilient modulus test)
- Microsensors to measure pavement roughness and temperature
- Crack monitoring of bridges
- Temperature monitoring of bridges during the winter to alert drivers to the condition of bridges
- Electromechanical sensors to detect and monitor corrosion in steel structures, especially welding joint and load transfer devices in rigid pavements

- Microfluidic applications to identify the alkali-silica reaction in concrete structures
- Microcrack monitoring in concrete
- Monitoring geotextile performance within pavement systems
- Reliability of welding units in structural steel
- “Smart Pebbles” – long-life wireless sensors that continually monitor the health of concrete bridge structures from deep inside the bridge deck
- “Smart Aggregates” – Embedded wireless sensors to measure pH, moisture, temperature, and concentrations of chloride, sodium, and potassium ions within the concrete
    - Temperature measurements during placement and curing for monitoring uniformity of the concrete mix, rate of the hydration reaction, and potential for thermal cracking using a well-distributed network of temperature sensors
    - Electronic pH sensors for detecting and identifying several deteriorations in concrete structures, including the presence of chloride ions, carbonation, and leaching of calcium hydroxide
    - Assessment of overall durability and strength of concrete using moisture sensor measurements
    - Investigation of the mixing process leading to optimization of mix designs and mixers
    - Measurement of subsequent compaction and shrinkage after placement of concrete
- Monitoring temperature, moisture, and early age shrinkage stresses in concrete
- Measurement of large-scale strains in soil foundations

However, significant challenges must be addressed to realize the full benefit of MEMS technology for real-time or quasi-real-time monitoring and assessment of transportation infrastructure. First, MEMS products are not generic, but application-specific. Issues like survivability of sensors and materials for long-term stable operation need to be evaluated. The impacts of embedding the sensor on the performance of a structure and vice versa need to be assessed. Also, there is the need to answer questions such as “Where is the optimal location of the device?” and “How many must be installed within a given volume/area of infrastructure for reliability?”

Objectives

The primary objective of this research was to investigate the use of MEMS in highway pavement infrastructure for SHM purposes. This study focused on investigating the use of MEMS and their potential applications in portland cement concrete (PCC) through a comprehensive literature review, a vendor survey, and a laboratory study. These were the specific objectives of this study:

- Ascertain the “technology readiness level” of MEMS technology for deployment in highway pavement infrastructure through a comprehensive literature review and vendor survey.
- Demonstrate the feasibility of using off-the-shelf, market-ready, prototype MEMS in PCC in the laboratory to monitor the physical properties of concrete, such as temperature, moisture, and strain.
- Provide recommendations to the Iowa Department of Transportation (DOT) for future research and implementation of potential MEMS-based highway infrastructure applications.

The following were the proposed research tasks to accomplish the objectives of this proof-of-concept study:

- **Task 1**: Literature search and review on the use of embedded MEMS sensors for SHM of highway infrastructure

- **Task 2**: Laboratory testing of MEMS sensors and systems

- **Task 3**: Based on the results of previous tasks, propose a conceptual system for employing MEMS sensors for continuous monitoring of concrete pavements in the field

- **Task 4**: Provide recommendations to the Iowa DOT for future research and implementation of potential MEMS-based highway infrastructure applications

There are four major process steps in manufacturing MEMS: design, fabrication, packaging and testing. These steps determine the final product's performance and price (Attoh-Okine 2003). The process flow sequence for fabrication of MEMS devices is depicted in Figure 2.

It is important for SHM systems to have a low unit cost, easy installation and a user-friendly way to analyze data. MEMS fabrication can be complicated. Attoh-Okine (2003) explains: "For example, in the application of MEMS to condition monitoring of axle bearings in railway, the entire process comprises around 50 single steps, including 10 lithography steps. Twenty sensors were fabricated simultaneously at an estimated cost of around $150 per sensor (Peiner 2002)." (Attoh-Okine 2003).

In the civil engineering infrastructure, MEMS are being studied to evaluate their application for SHM. Some of these research projects are described in more detail later.

MEMS Applications in SHM and Concrete Monitoring

Although MEMS are new to the civil engineering industry, SHM has been of significant importance for several decades. Highway agencies have inspection and maintenance programs for both pavements and bridges. MEMS could potentially impact both pavement and bridge maintenance programs. The next several paragraphs explain the importance of good pavement and bridge management.

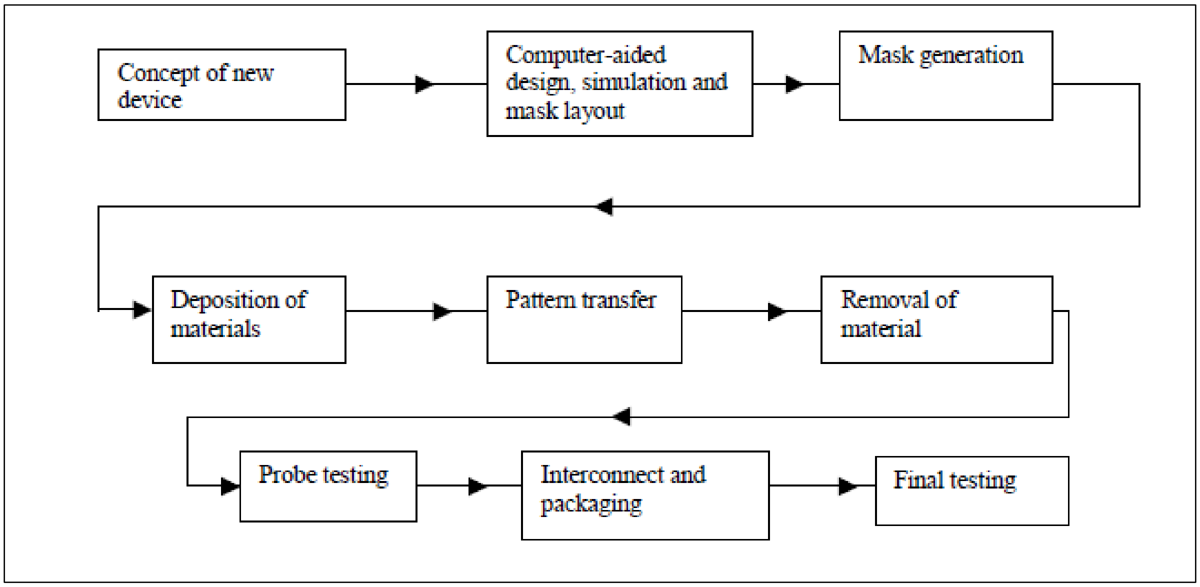


Figure 2. Process flow sequence for MEMS device fabrication (Tanner 2001, Mensah 2003)

Pavement management can be traced as early as the ancient Roman Empire, but pavement management on computer systems began during the 1970s. The computer systems helped engineers make discoveries about best practices for preventive maintenance and pavement management.

One of the important discoveries was pavement deterioration rate. Pavement tends to deteriorate very slowly during the first few years and very rapidly after it has aged. This shows that fixing the worst roads first is an expensive way to maintain a highway. The pavement management systems currently consist of a system that will regularly collect pavement condition data, a computer database to sort and store collected data, and an analysis program to evaluate repairs or maintenance strategies and to recommend cost-effective projects (FHWA 2008).

The possible benefits of MEMS have led to many research projects, which have tested, improved, or developed MEMS. Some of the highlighted research studies include the development of the Wireless Embedded Sensor Platform (WESP) at the John Hopkins University Applied Physics Laboratory (APL), Smart Pebbles at the California Department of Transportation (Caltrans) and SRI International, and more recently the Smart Pavement Monitoring System being developed at Michigan State University.

These research projects have the potential to help improve SHM, which is necessary for the aging infrastructure and the increased demand for efficient monitoring and maintenance. One way civil engineers will help to make monitoring and maintenance more efficient is to develop "smart structures," and some of these research projects bring the industry one step closer to practical use of them.

Importance of SHM

SHM has been a growing priority for the civil engineering infrastructure as the country's roads and bridges become older and need more maintenance attention. There are several SHM methods, but many prove to be time consuming and expensive.

In 2006, the Federal Highway Administration (FHWA) celebrated the 50th Anniversary of the Eisenhower Interstate System. This serves as a reminder of the upcoming challenges engineers face with an aging infrastructure. Efficient SHM for bridges and pavements will aid engineers in identifying developing distresses and in scheduling maintenance early. "The bridge management systems of the future must be based upon better information, better knowledge, better technology, and improved decision support tools," explains Carl Ealy of the FHWA (FHWA 2006).

As history shows, SHM is important for the nation's highway and bridge system. The book, *Smart Material Systems and MEMS* (Varadan et al. 2006), identifies three levels to SHM:

- Level 1 - Confirming the presence of damage
- Level 2 - Determination of the location, size, orientation of the damage
- Level 3 - Controlling the growth of damage

The most-commonly-used damage-detection methods rely on subjective, incremental, visual assessments or localized testing, such as eddy current, ultrasonic, acoustic-based sensing, strain monitoring, corrosion monitoring, and others (Phares et al. 2005).

Importance of Concrete Monitoring

Many of the monitored structures in the civil infrastructure are made out of concrete. Concrete's properties, like strength and durability, depend heavily on temperature and moisture. A rapid loss of moisture can lead to a lower strength development, which can lead to early damage to a structure (Saafi and Romine 2005). Monitoring temperature and moisture distribution in concrete structures will help engineers determine concrete strength and the severity of shrinkage cracking (Saafi and Romine 2005).

MEMS embedded in concrete could help engineers to more efficiently monitor the curing process of concrete. These properties are important because understanding the rate of drying is useful in determining the properties or physical condition of the concrete (Kosmatka et al. 2002). Concrete needs moisture to cure and, if moisture is not present, concrete ceases to gain strength.

Smart Systems and Smart Qualifications

In the report, *Health Monitoring of Bridges, Structures and Components Using Smart-Structure Technology*, a detailed description is given of the attributes that must be incorporated into a health monitoring system to be considered "smart" (Phares et al. 2005). The following definition from the report is the one used for this literature review:

> A "smart" technology is one in which "the system systematically reports on the condition of the structure by automatically making engineering-based judgments, records a history of past patterns and intensities, and provides early warning for excessive conditions or for impending failure without requiring human intervention." These features make the system capable of providing and "facilitating self-diagnostic, real-time, continuous sensing, advanced remote sensing, self organizing, self identification, or self-adaptation (decision-making and alarm-triggering) functions." Furthermore, the user is not burdened with demanding operational and maintenance tasks (Phares et al. 2005).

Strictly speaking, none of the monitoring systems reported in the literature (at least until 2005) meet all of criteria for a true smart SHM system, based on this definition. One system has the title "smart sensor" on their product, but it doesn't fulfill all of the above requirements. It is important that a universal definition of "smart" be adopted by the engineering community. This will allow for everyone to have a well-defined, common goal. There are many challenges in the area of smart structures, especially the ability to provide reliable real-time continuous monitoring.

Active and Passive Sensors

In the white paper, *RFID, MEMS, and Their Application in the Field of Construction*, the difference between active and passive radio-frequency identification (RFID) tags is described. Essentially, the same definition can be applied to MEMS. A passive sensor system requires the use of a reader or interrogator to transmit an electromagnetic field to activate the sensor to begin transmitting data (Durfee and Goodrum 2002). When the reader is not activating the electromagnetic field, the sensor does not transmit any data, nor is it using any power.

Active sensors are equipped with an internal battery that transmits information to the reader at a specified time interval. Active sensors are generally more expensive, larger in size, have a life span limited to the internal battery power supply, have a higher memory capacity, and information can be sent from the sensor to the reader and vice versa (Durfee and Goodrum 2002).

Communication between the reader and the sensor can be a significant benefit because it gives the engineers the ability to change the frequency the sensor sends data or change the way data is processed. Changing the way and frequency data is processed and received gives the sensor system the ability to better adapt to the constantly changing environment. For example, if an extreme event occurred and there were questions about the structural integrity of a bridge, the monitoring frequency for that structure could be increased to better monitor the structure's condition.

The Importance of Wireless Network Systems

For MEMS to reach their full potential, there must be efficient communication between the SHM sensors and the computer, where an engineer can interpret the collected data. Many of the systems used to monitor structures are wired. Wired systems are relatively expensive and time consuming to install (Kruger et al. 2005). The difficulty of transporting data has been a largely unaddressed problem (Varadan and Varadan 2000).

Wireless network systems are becoming more established. There are companies that have wireless network systems for monitoring environmental attributes. Wireless systems will potentially improve sensor systems in the areas of data aggregation, signal analysis, sensor clustering, event localization, time synchronization, measurement progress, discrete monitoring, and event-based monitoring (Kruger et al. 2005). These systems are discussed in greater detail later.

The Role of Sensor Size

In some cases of SHM, MEMS have advantages over the larger sensors because they have a smaller form factor and consume less power than other types of sensors (Chung et al. 2005). The size of the sensors dictates a number of different properties of the entire sensor system. Some of the attributes that size controls are the density of the sensor system, the material costs, the power demands, and the packaging costs. The smaller sensors will provide a competitive edge as well as many benefits resulting from their smaller size.

Real-Time Monitoring

The capability to have real-time monitoring in structures is important because it allows engineers to have event-triggered alarm systems that can tell engineers when an extreme event has exceeded a particular threshold in the sensor system. In addition, tracking day-to-day properties of a structure is useful when observing what is happening within a structure over a long period of time.

Real-time monitoring was important to engineers who worked on a wireless sensor system called Dura Node. Dura Node developers emphasized that a time-triggered operation mode, as well as an event-triggered mode, in which data is transmitted only when a threshold is exceeded, are desirable properties in a sensor system (Chung et al. 2005).

The Future of SHM

The field of SHM will continue to grow. SHM has applications in many fields, such as the aerospace and automotive industries. A study in 2005, funded by the Wisconsin Highway Research program, was conducted by the Center for Transportation Research and Education (CTRE) at Iowa State University (ISU) on the types of smart monitoring technologies available and what technologies will be available in the future.

The emerging technologies mentioned are fiber optic sensors, MEMS, wireless sensors for corrosion monitoring, wireless communication, data processing, and data management. Some of these technologies depend on other emerging technologies. For example, it is necessary to have efficient data processing and management for a MEMS to operate in the way designers intend.

The Wisconsin Highway Research program study also revealed that current use of actual smart systems was not widespread throughout state DOT agencies (Phares et al. 2005). As MEMS and wireless technologies improve, more sensor systems will be added to the list of "smart" sensor monitoring systems. The envisioned future for MEMS is to integrate microsensors, microactuators, and microelectronics and other technologies onto a single microchip, which will enable the development of smart products and the realization of complete "systems-on-a-chip."

MEMS, Nanotechnology, and NEMS

The National Nanotechnology Initiative (NNI) defines nanotechnology as involving research and development at the atomic, molecular, or macromolecular levels in the sub-100-nm range to create structures, devices, and systems that have novel functional properties. However, some scientists consider this definition restrictive and would like to refer to nanotechnology as an umbrella term to define the products and processes at the nano/micro scale that have resulted from the convergence of the physical, chemical, and life sciences.

Nanotechnology is a rapidly-evolving field and is finding newer and newer applications in the engineering domain. The US National Science Foundation (NSF) predicts that by 2015, the annual global market for nano-related goods and services will exceed $1 trillion, making it one of the fastest-growing industries in history.

The distinction between MEMS and nanotechnology is often not so clear, although they are cited as separate technologies. In reality, they have overwhelming mutual dependencies and, this trend is expected to increase as these and other related technologies evolve with time. Nano-electromechanical systems (NEMS) devices are similar to MEMS with typical device dimensions in the nanometer range.

Civil engineering infrastructure is one area where nanotechnology has great potential. According to a recent feasibility study published by Saafi et al. (2010), embedded wireless MEMS and nanotechnology-based sensors have the potential to form self-sensing concrete structures that could detect the early formation of tiny cracks and measure the rate of temperature, moisture, chloride, acidity, and carbon dioxide levels, etc., each of which might reflect a decrease in structural integrity.

Recent Research on MEMS and Sensor Systems for Infrastructure Monitoring

MEMS integrated in a wireless network can help to make a low-cost, manageable way to monitor the nation's bridges. This section discusses some of the systems that are currently being developed and a few that are commercially available.

The passive systems presented are the MEMS Concrete Monitoring System from Advanced Design Consulting (ADC) USA, Inc., the Wireless Embedded Sensor Platform (WESP) from the John Hopkins University Applied Physics Laboratory (APL), and Smart Pebble from Caltrans and SRI International. All of the passive systems are in the prototype stages. The two active systems are from Crossbow Technology, Inc. and Sensicast. Both of these systems are available commercially.

ADC MEMS Concrete Monitoring System

ADC of Lansing, New York has recently developed the prototypes of the MEMS Concrete Monitoring System. ADC claims it has successfully integrated the temperature, humidity, and moisture sensors to the RFID system using a modular systems approach.

This concept is similar to a personal computer (PC) motherboard integrated with sound card, video card, etc., with different functionalities. Together with the sensors, a number of Radio Frequency (RF) antennas are also integrated to transmit the wireless signal when queried using a RFID communications system. Figure 3 shows the sensors are approximately the diameter of a quarter and they combine RFID with MEMS in a package that can withstand being mixed with concrete (Advanced Design Consulting 2008).

Figure 3. ADC's MEMS concrete monitoring system (ADC)

John Hopkins University Applied Physics Laboratory WESP

The John Hopkins University Applied Physics Laboratory (APL), with help from the Maryland State Highway Administration, has developed a passive wireless sensor system (Wireless Embedded Sensor Platform or WESP). It is designed to be embedded into concrete and take sensor readings from within a bridge deck (Darrin et al. 2004). Because it is a passive sensor, there is no internal battery and the device is powered when the user places a coil carrying an electric current in the proximity of the instrument that is embedded in concrete (Srinivasan et al. 2005).

The reader can send the data to a data logger or PC for analysis. The miniature wireless EIS sensor has been tested, so far, in three different mediums: concrete, water, and coatings. In addition, the sensor was tested against a simple resistor-capacitor (RC) circuit. According to Rengaswamy Srinivasan of John Hopkins University APL, the WESP has been tested and proven for the following applications: corrosion rate sensor, conductivity sensor, coating heal monitor (CHM), and water corrosivity monitoring (WCM). And, they are continuing to develop other applications for the WESP sensor system.

The packaging for the WESP system needed to withstand being embedded in wet concrete as well as hold up to the pressure from curing, freeze/thaw cycles, and traffic loading. Ceramics were the material chosen for the packaging and it was also important for the ceramic's coefficient of thermal expansion to closely match that of concrete (Carkhuff and Cain 2003).

As Figure 4 shows, each WESP sensor contains a wireless power receiver and data transmission coils. To sustain concrete's harsh environment, (including mechanical stresses and high pH), the sensor is designed using ceramic hybrid integrated circuit technology.

The WESP sensors have a projected lifetime of 50 years. The long lifetime is achievable because the wireless power transmission allows the embeddable sensors to remain maintenance free. Prototypes of the WESP system that include sensors have been created and the reliability of this system is being tested (Kuennen 2004).

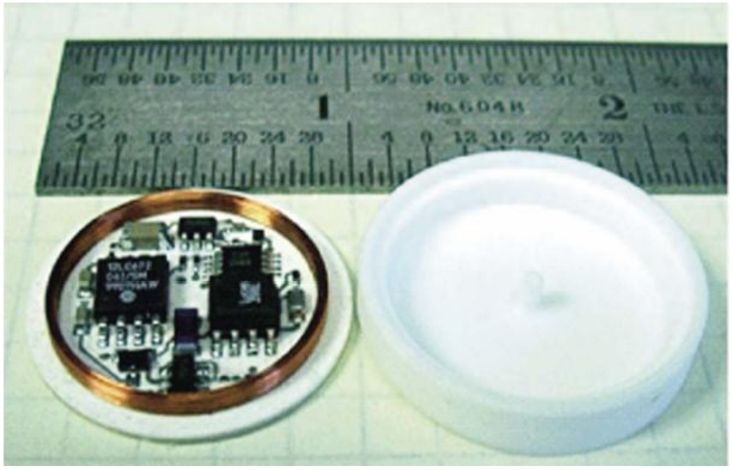


Figure 4. The wireless embedded sensor platform (WESP) (Darrin et al. 2004)

Smart Pebbles

Smart Pebbles were being developed by SRI International in Menlo Park, California for Caltrans. The smart sensor is a wireless passive sensor that is approximately the size of a piece of gravel. The SRI team built the device by linking a new type of chloride sensor to an off-the-shelf wireless communications chip and packaging it with cement-like materials. Figure 5 shows an illustration of the Smart Pebbles concept.

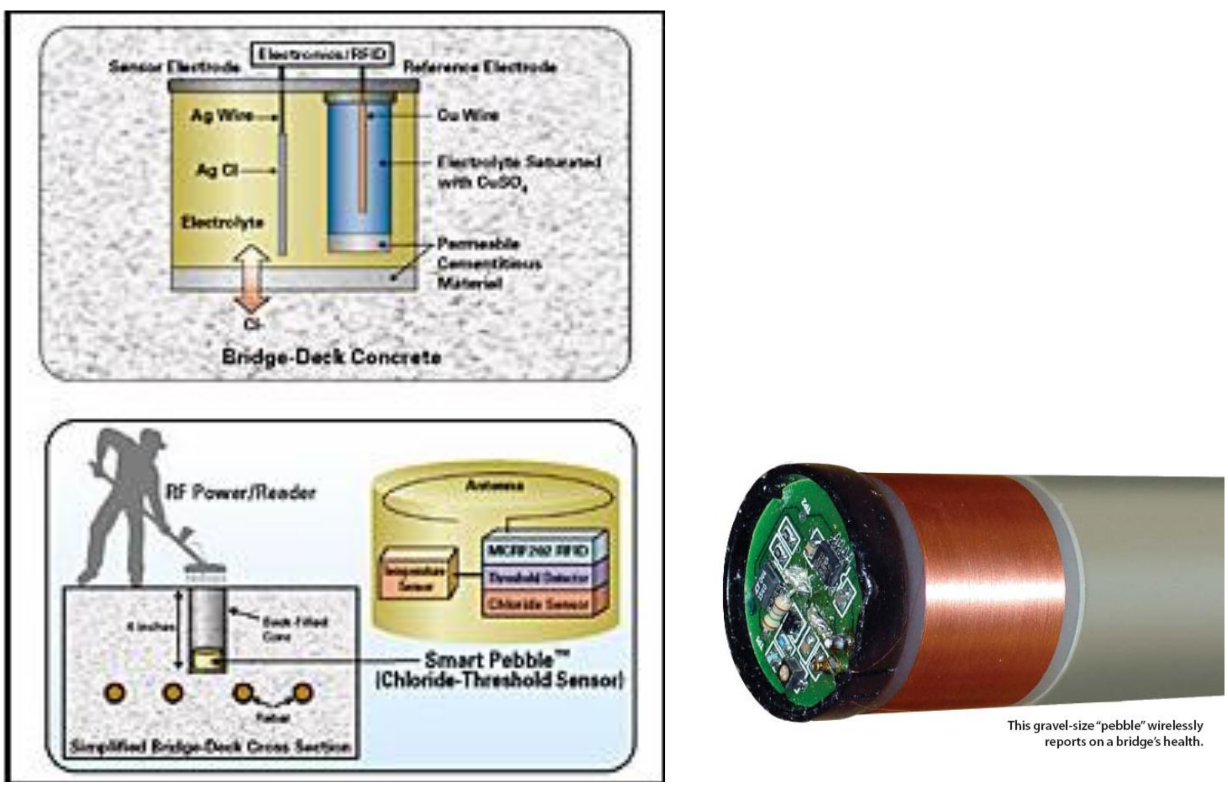


Figure 5. Smart Pebble concept (Watters et al. 2003, Technology Review 2003)

The sensor develops a voltage that is dependent on the salt concentration. This helps indicate if reinforcing bars are corroding (Technology Review 2003). Currently, no future developments are underway for the Smart Pebble sensor.

Hygrometrix Sensors

The MEMS sensors manufactured by Hygrometrix were used in research projects for monitoring temperature and humidity. Hygrometrix is no longer in service and they sold their products to Centric, Inc.

The device that is available is a MEMS sensor that can measure temperature and humidity in a packaging that allows the sensor to be embedded in concrete. There are currently no RFID capabilities, but it could be a future possibility.

For proof-of-concept purposes, a wired connection was used in the research done by Saafi and Romine (2005) at the Center for Transportation Infrastructure Safety and Security at Alabama A&M University. A wired connection also allowed for continuous monitoring of the sensor outputs (Saafi and Romine 2005).

The Hygrometrix HMX2000-HT sensors were calibrated and each MEMS sensor had special packaging that allowed for them to be embedded in concrete. This experiment used concrete cylinders of 152x305mm with a water to cement ratio of 0.45 and 0.53 to evaluate the sensor's performance. Based on the results from the experiment, the MEMS survived the concrete's corrosive environment and internal and external stresses.

The sensor outputs report the concrete's change in properties and the Hygrometrix sensor can be used to measure moisture content, temperature, and shrinkage-induced stresses (Saafi and Romine 2005). Figure 6 shows the MEMS sensors that were used and Figure 7 shows the Hygrometrix P-12 packaging that allows the MEMS sensors to be embedded in concrete. The P-12 packaging has a total height of .6565 in. including the prongs and the head has a diameter of .323 in.

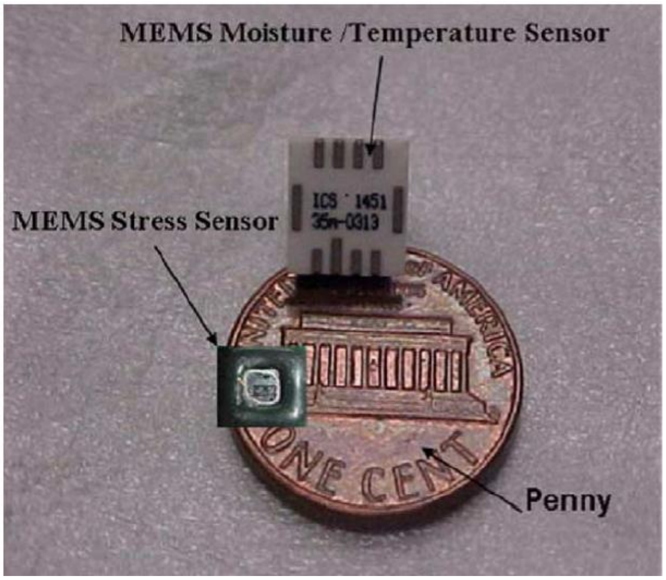


Figure 6. MEMS devices for early age concrete property monitoring (Saafi and Romine 2005)

Figure 7. P-12 packaging (Centric, Inc.)

Crossbow Technology, Inc.

Crossbow Technology, Inc. is a company based out of San Jose, California. They have a close working relationship with Intel Corporation. Crossbow manufactures three main types of products, which include wireless sensor networks, inertial systems, and ēKo PRO Series (environmental monitoring). This summary focuses on Crossbow's wireless sensor network systems.

Crossbow's wireless sensor network consists of active sensors complete with sensor boards. The sensor boards are the sensing part of the unit. Information is collected by the sensor node and the data is transferred wirelessly to the base station, which connects directly to a laptop or a data logger. Crossbow provides monitoring software that allows for historical and real-time charting. The software also allows for mote programming and command interface to sensor networks (Crossbow Technology, Inc. 2007).

There are several research projects that have used the wireless sensor networks from Crossbow for monitoring bridges. One university that has done significant research using the Crossbow sensor system is the University of Illinois at Urbana-Champaign (UIUC). B.F. Spenser, Jr. and UIUC graduate students have done several studies using Crossbow sensor systems.

A couple of the documents reviewed were *Structural Health Monitoring Using Smart Sensors* (Nagayama and Spencer 2007) and *Structural Health Monitoring Sensor Development for the Imote2 Platform* (Rice and Spencer 2008). Both papers gave more insight into how the Crossbow sensor works, as well as explain some of the challenges that come with sensor systems, such as time synchronization, reliability, and sampling frequency, as well as the power consumption associated with sampling rates.

There are a number of different types of sensor platforms available from Crossbow, such as the Imote, Imote2, MICA, MICA2, MICAZ, MICA Dot, and IRIS.

The sensors are active, which means they transmit a sensor reading at a user-specified frequency. For example, engineers can decide if they would like a sensor reading to be taken every 30 seconds or every two minutes. An internal battery is the sensor's power source. This allows for users to retrieve data remotely (but the battery will eventually need to be replaced).

The frequency at which the data is transferred is a major factor in how much power the sensor system consumes. The higher the frequency for the data transfer rate, the sooner the batteries will need to be replaced.

Figure 8 shows how the network architecture works. The sensors send data to a base station that is connected to a computer and the internet. This allows for the information to be accessed from anywhere via the internet. The next several paragraphs give more information about the sensor nodes and the base stations.

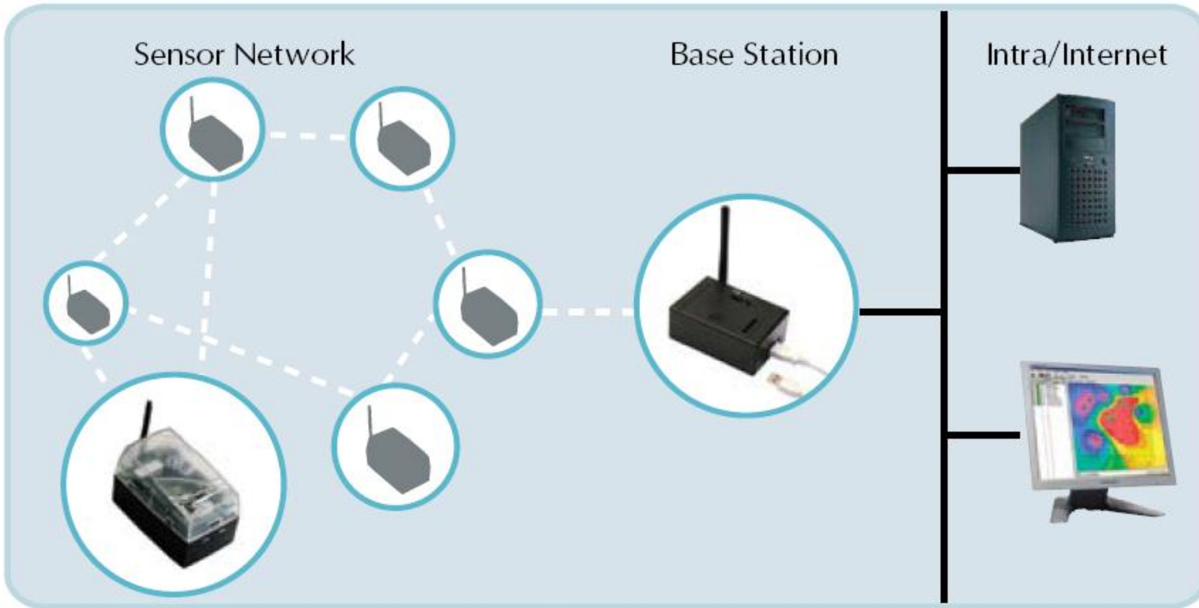


Figure 8. Crossbow's network architecture for the professional development kit (Crossbow Technology, Inc. 2007)

The sensor node is shown in Figure 9. The sensor node consists of a processor, radio board, and sensor board. There are several different types of sensor boards. The common properties that are measured by sensor boards include temperature, humidity, barometric pressure, acceleration, and ambient light (Crossbow Technology, Inc. 2007).

Figure 9. Crossbow sensor node with sensor board (Crossbow Technology, Inc. 2007)

The base station is shown in Figure 10. The two major components of the base station are the processor/radio board and a Universal Serial Bus (USB) PC interface board. The base station connects directly to the computer and collects all the data that are sent by the sensor node. The

USB PC interface board in the professional kit is the MIB520 Gateway, which provides a USB interface for data communication.

Figure 10. Crossbow base station (Crossbow Technology, Inc. 2007)

Crossbow has a large selection of different types of sensor systems. This versatility is an advantage in SHM. There are many different attributes that need to be measured in a structure and this system has the capability to measure many of the structure's properties, while keeping all of the sensors on the same network. Individuals monitoring the roads or structure will be able to access real-time data remotely. As more research and development is done, it's possible that the size of these sensors will become smaller, which will allow for many other applications.

Sensicast

Sensicast is a company based out of Needham, Massachusetts. They specialize in wireless sensor networks that can be used for a variety of applications without complex set up or integration. They also specialize in industry solutions and will design sensor systems that meet specific requirements for applications that demand high reliability, high data accuracy, and flexible storage and retrieval of network data (Sensicast 2008).

The three main components of the Sensicast wireless network system are the "Smart" Sensor, Mesh Router, and Gateway. This sensor system consists of active sensors that have an onboard battery and they automatically send a reading at a specified interval of time. Figure 11 shows how the wireless system can be set up and some of its applications. The sensors can be used or modified to measure many different properties, which include, but aren't limited to, current, humidity, pressure, temperature, vibration, contact closure, power, level, and flow.

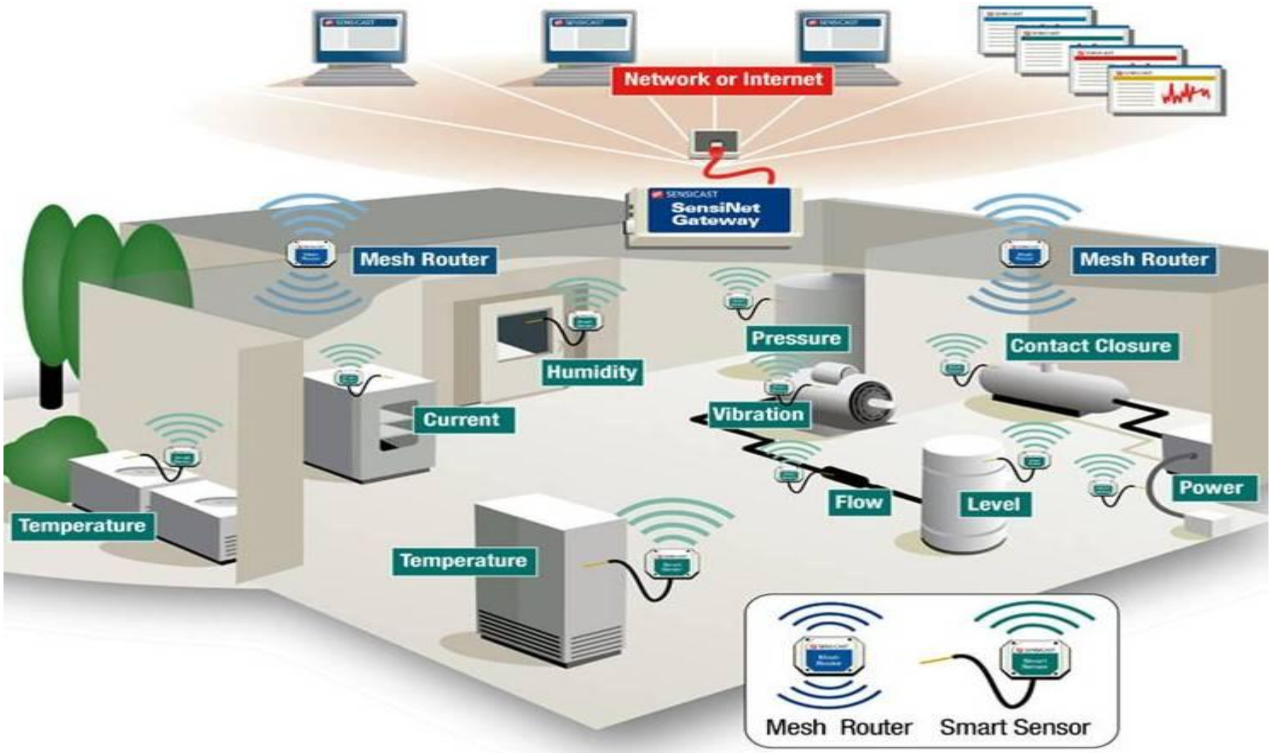


Figure 11. Sensicast wireless network system (Sensicast 2008)

The figure helps show how the signal is transferred to the mesh router and, to allow for a more reliable network, the mesh router sends the signal to the SensiNet Gateway, which is connected to the internet and allows engineers to review the sensor data remotely.

The sensors cannot be directly embedded into concrete. External sensor probes or tethers are used as shown in Figure 12. The typical dimensions for the "smart" sensors are approximately 3.5x5.5x1.4 in.

Figure 12. Sensicast temperature and humidity sensor with tether (Sensicast 2008)

There is special packaging for the Sensicast sensors that protect sensors exposed to high-moisture environments. The packaging is made from a polycarbonate packaging with neoprene seals and the dimensions are 6.3x6.6x2.4 in. This type of packaging will be necessary for most sensors used in the civil engineering infrastructure.

The sensor shown in

Figure 12 is similar to other Sensicast sensors. The one shown measures temperature and humidity, but there are many sensor applications available.

Figure 13 shows the Mesh Router. The router is used to extend the reach of the entire network system by receiving and re-routing messages through the network. The dimensions are 3x5x1.5 in. The Mesh Router increases systems reliability, it is able to run on AC or DC power, and it has battery backup capabilities.

Figure 13. Sensicast Mesh Router (Sensicast 2008)

Figure 14 shows the Sensicast Gateway. The Sensicast Gateway manages the network and allows access to the data collected by the sensors. Each gateway can manage 50 Sensicast sensors. The data displayed can be the current data as well as previously-collected data, so engineers can track what is occurring over time. The gateway is programmed for basic network functions, such as creating the rules behind triggers and alerts (Sensicast 2008). The dimensions for the Sensicast sensors are somewhat large, not embeddable, and there is not a microprocessor within the sensor. For these reasons the Sensicast system was not tested for this laboratory project.

Figure 14. Sensicast Gateway (Sensicast 2008)

Bridge Health Monitoring Using Wireless Sensor Network (WSN)

The researchers at the University of California at Berkeley experimented with a MEMS they call Motes (see Figure 15). They actually deployed a Mote network for testing on the Golden Gate Bridge (GGB) (Pakzad 2008).

Figure 15. Mote (MEMS) sensor (Kim et al. 2006)

The Golden Gate Bridge now has an experimental sensor network of approximately 200 small Motes, each with an accelerometer that measures movement such as traffic, wind, or seismic loads. To identify the vibration characteristics, a 64 node wireless network was deployed for the main span (4,200 ft) and south tower (690 ft) of the GGB (see for the instrumentation plan in Figure 16).

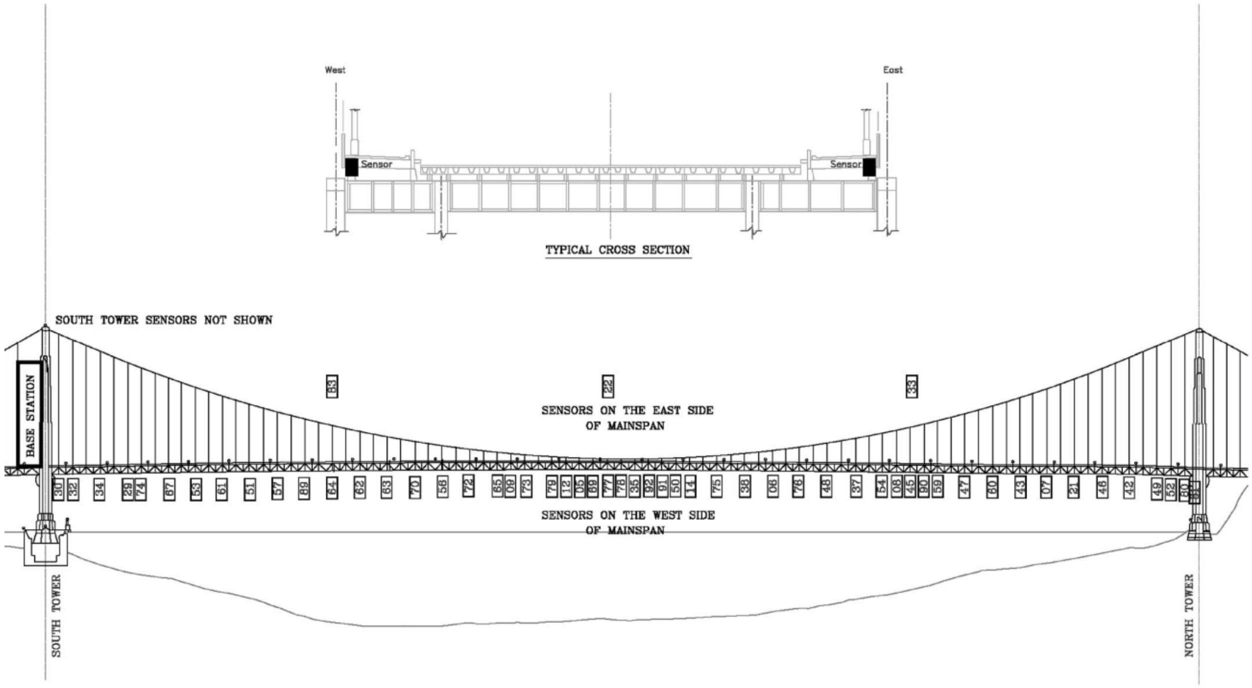


Figure 16. Instrumentation plan for 56 nodes on the Golden Gate Bridge's main span (Pakzad et al. 2008)

The following were the primary goals (Kim et al. 2006): (1) to determine the response of the 70 year old structure to ambient and extreme conditions, (2) to compare actual behavior to design prediction, and (3) to test the scalability and performance of the Wireless Sensor Networks (WSN). One of the sub-goals was also to create a three-dimensional picture to portray structural abnormalities when all sensor readings are correlated.

The sensor node consisted of a 16 bit ADC MicaZ Mote with an 8 bit, 8 MHz controller and 512 kB flash memory, and a 2.4 GHz radio transceiver with a bi-directional antenna. Two models of accelerometers were used in this application: a large range accelerometer (±2 g with a sensitivity of 1 mg at 25 Hz) for earthquakes and a more-sensitive low-range (10 μg) accelerometer for measuring ambient vibrations due to wind and traffic. A 1k Hz Sampling rate was used (Xue et al. 2008).

Wireless Nanotube Composite Sensor for Concrete Crack Detection

Saafi and Kaabi (2009) propose the concept of using wireless and embedded nanotube sensors in concrete structures for structural integrity monitoring. An in situ, wireless, and embedded sensor for detecting cracks in concrete structures was developed by the authors by embedding carbon nanotube (CNT) networks into a cement matrix. The changes in the electrical resistance of the CNT networks were measured wirelessly to monitor and detect the progression of damage in concrete.

Portland cement (ASTM type I), untreated single walled nanotubes (SWNT) (purchased from NanoAmor, Inc.), and thin copper electrodes were the raw materials used to manufacture the cement CNT sensors. Figure 17 depicts the fabrication process of these sensors, as well as the typical dimensions.

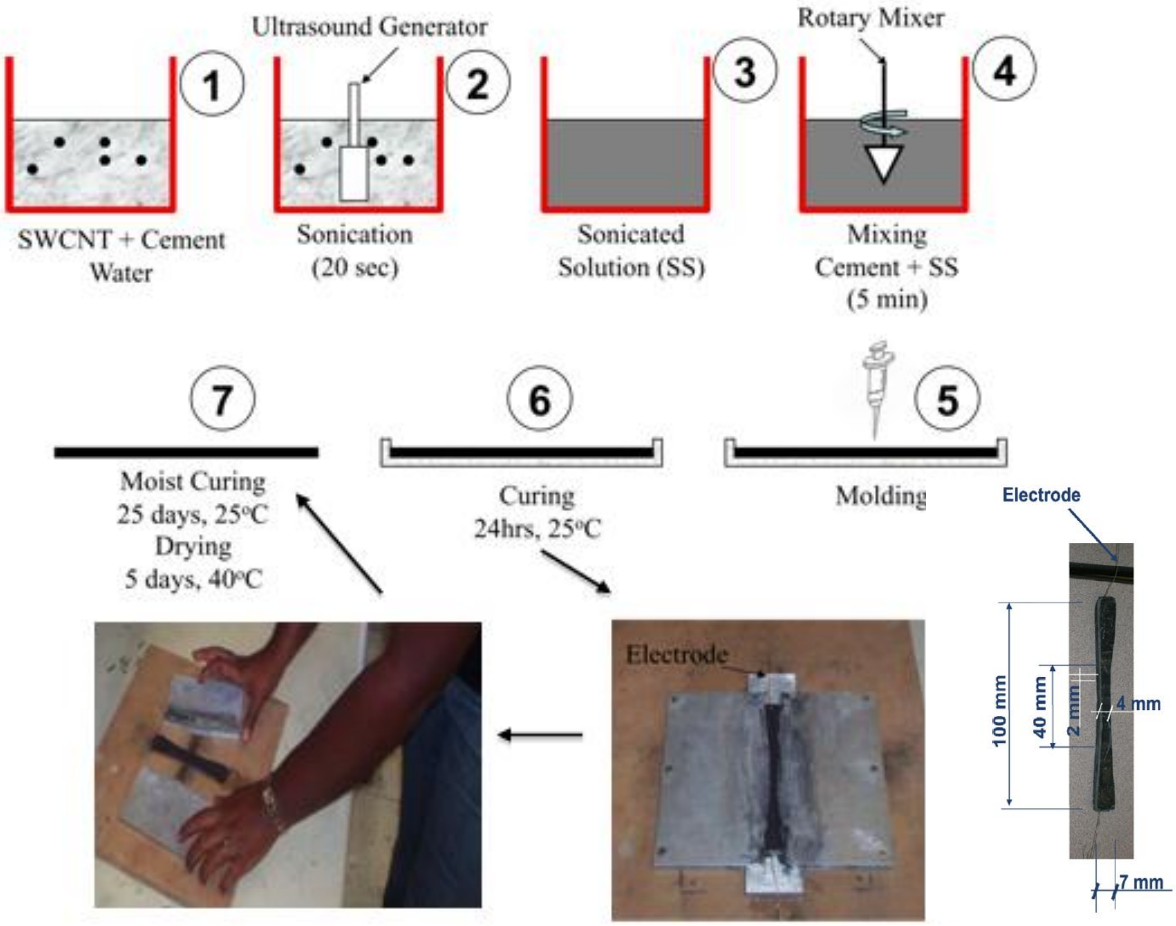
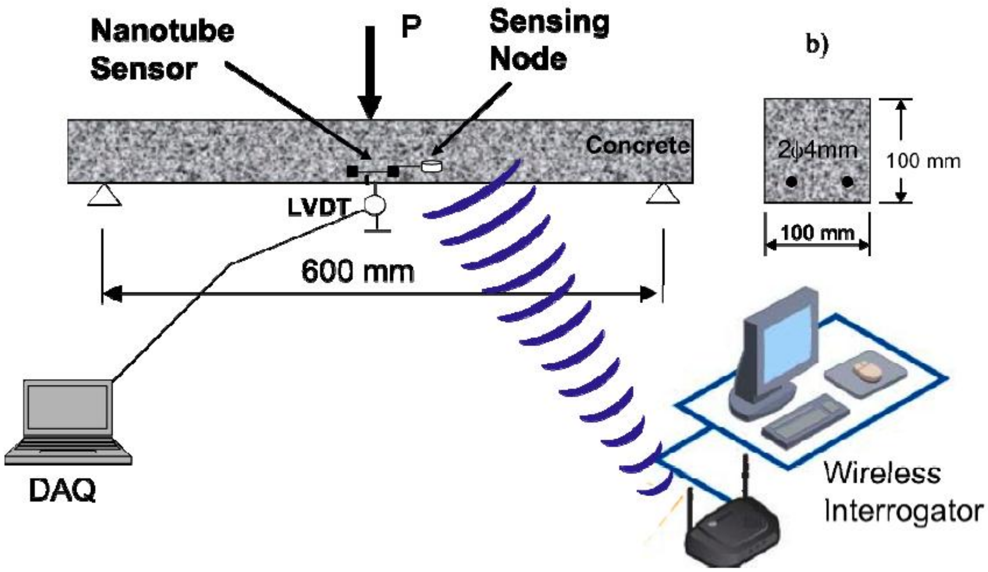


Figure 17. Fabrication of cement CNT sensors (Saafi and Kaabi 2009)

An off-the-shelf, low-cost, wireless communication system was used to measure the response of the embedded cement CNT sensor (see Figure 18). The wireless monitoring system was designed and provided by Microstrain, Inc. The wireless response of the cement CNT sensors embedded into the concrete beams described well the behavior of the concrete beams in terms of crack propagation through change in effective response (Saafi and Kaabi 2009).



(a)

(b)

Figure 18. (a) Wireless monitoring process (Saafi and Kaabi 2009), (b) EmbedSense wireless sensor (MicroStrain, Inc. 2011)

Ong et al. (2008) developed a wireless, passive, embedded sensor for real-time monitoring of moisture content in civil engineering materials, such as sands, subgrade soils, and concrete materials. The water-content monitoring sensor was based on a passive, wireless inductor-capacitor (LC) resonant circuit (see Figure 19), which, when embedded in test samples, remotely measures the internal water content of samples by tracking the changes in the sensor's resonant frequency.

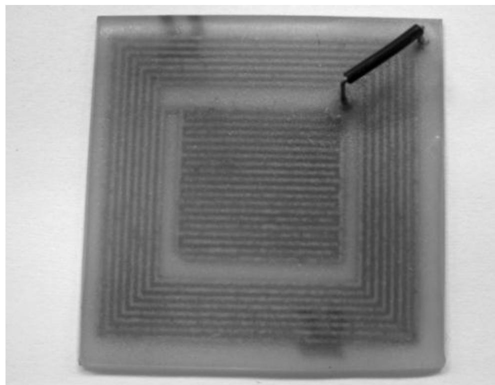


Figure 19. Wireless inductor-capacitor (LC) sensor, which comprises of a serial LC circuit printed on a substrate (Ong et al. 2008)

The importance of monitoring moisture content in water-permeable civil infrastructure cannot be underestimated. It is important to accurately determine the water requirement of the PCC mixture to ensure its long-term reliability. In the case of asphalt mixtures, the presence of unwanted moisture leads to stripping and debonding of asphalt and aggregate particles. In buildings, excessive humidity and damped environment are the leading causes of mold growth, which is a serious environmental health issue.

The LC sensor was made of a single-sided printed circuit board and the inner and outer lengths of the square, seven-turn spiral inductor were 1.0 in. (2.5 cm) and 1.5 in. (4.0 cm), respectively. One of the experiments carried out in their research involved determining the curing and drying rate of cement concrete after exposure to water. The changes in the sensor's resonant frequency over time during the curing of PCC is shown in Figure 20.

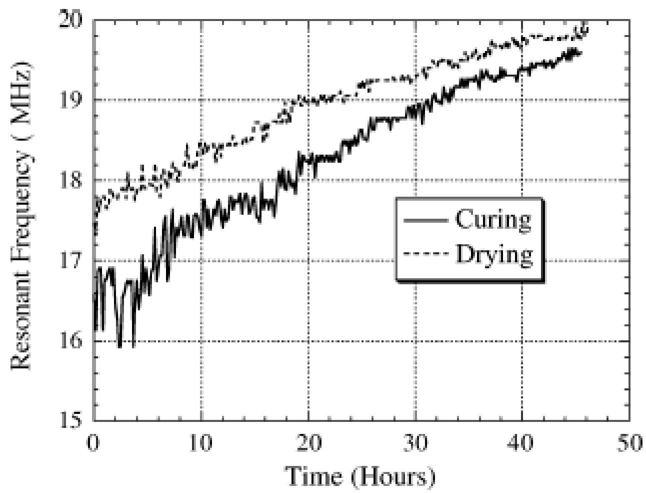


Figure 20. A typical resonant frequency response of the LC sensor during the curing and drying of the concrete sample (Ong et al. 2008)

Ong et al. (2008) identified several potential applications of the LC sensor in civil engineering projects:

- Monitor trapped water in asphalt pavement resulting from precipitation, snowmelts, subsurface water tables, and runoff, allowing for effective management, rehabilitation, and maintenance.

- Detect trapped water and ice lenses within a bridge deck (slab) and establish the weak spots (water construction zones) in concrete components of bridge structures.

- Monitor water trapped in pavement substructures (base, subbase, subgrade, and pile structures), which cause frost-heave issues, subsurface erosion, pavement depression, and loss of structural integrity.

- Determine water penetration in hydraulic structures, such as dams and flood-restraining embankments.

PaveTag

Minds, Inc. has introduced a new application that employs RFID technology to track hot-mix asphalt from the time it leaves the plant to when it arrives at a construction site and is dumped into a paver. PaveTag (part of the eRoutes suite of automation systems) uses battery-assisted passive (BAP) ultra-high frequency (UHF) RFID tags (from IDENTEC SOLUTIONS) affixed to the trucks that transport the hot asphalt from the plant to the site. The overall process flow of the PaveTag technology is illustrated in Figure 21.

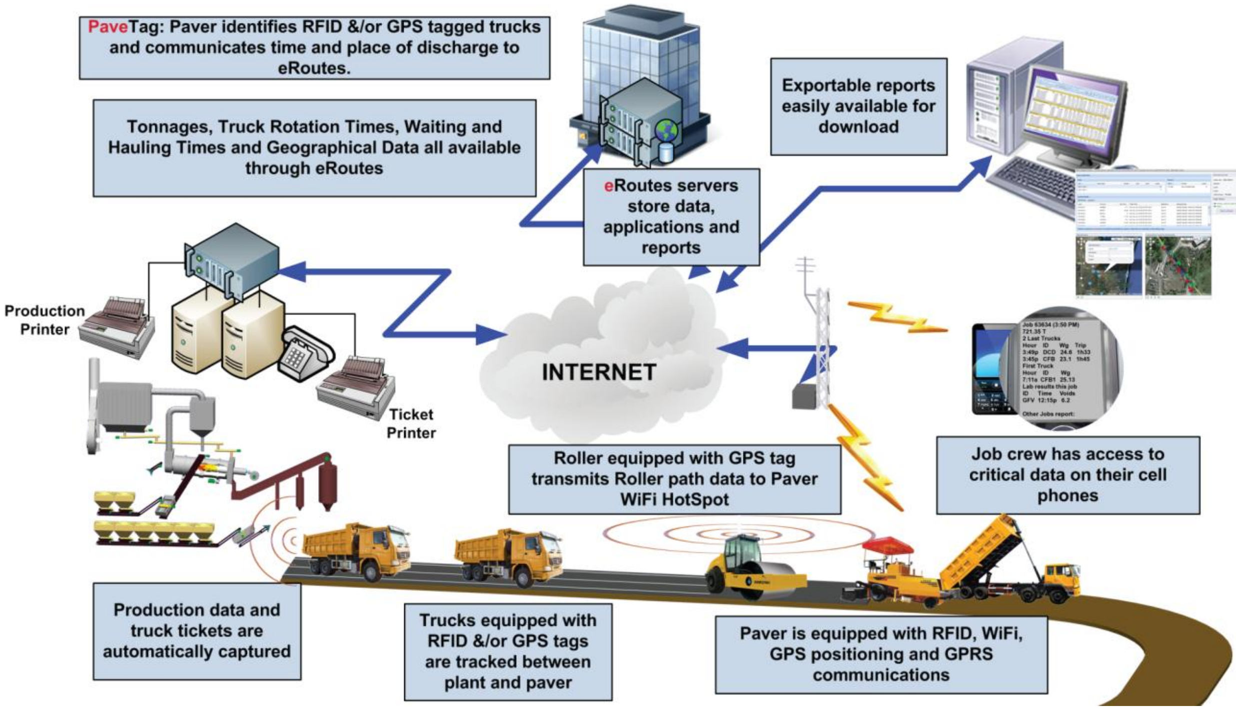


Figure 21. PaveTag technology (Minds, Inc.)

The PaveTag system provides the user with the following for each load:

- Time of arrival at plant
- Ticket content capture at time of loading
- Time of departure from plant
- Total time at plant
- Time of travel
- Truck route follow up on map (PaveTag GPS)
- Time of arrival at job
- Time of arrival at paver (PaveTag RFID)
- Exact location of dump on map (PaveTag RFID)
- Time of departure from paver (PaveTag RFID)
- Time of departure from job
- Total time at job
- Total tons, cycle times, transport time, waiting time per job, hauler, truck

Future of MEMS, Challenges, and Recommendations

It has been reported that MEMS are on course to revolutionize SHM and infrastructure management. MEMS sensors have become a reality in today's world, although there are still many developments needed in order to implement this technology.

There are different challenges for each different type of system. The passive systems present challenges with wireless interrogation. These challenges include power transfer, data storage, and processing (Norris et al. 2006). One of the issues that both active and passive systems face is durable packaging that still allows the system to be cost effective. Packaging remains to be application-specific and the cost can vary between 75 and 95 percent of the overall cost (Attoh-Okine 2003).

The small size and ability for bulk production works as an advantage for MEMS. The small size means less material is needed for packaging and bulk production allows the sensors to be manufactured at a low unit cost. For example, the WESP system has been projected to cost as little as $10 per unit (Cain et al. 2001). Reliable MEMS sensor systems at low costs would have the ability to change day-to-day SHM practices.

As these systems become more available, we will begin to see an increase in smart structures and roads that could help engineers make better-informed maintenance decisions and ensure the safety of the traveling public. Despite the many challenges, there are some sensor systems, like Crossbow's, that are commercially available. To overcome many of the challenges research to improve the MEMS sensors will continue.

MEMS applications vary immensely and the multidisciplinary nature of these sensor systems allow engineers with different backgrounds to collaborate on the same research projects. A diverse research team will help in developing more useful applications for MEMS while the challenges are overcome.

Many challenges with MEMS systems remain primarily in the sensor systems that transfer, relay, and process data (Saafi and Romine 2005). The top four challenges to overcome are packaging technology, energy supply, internal and external methods of communication within the micro-system, and signal possessing and control (Ko, 1996).

One new development is showing promise in the area of energy supply. Although a number of potential self-powering energy sources have been identified (e.g., solar power, thermal gradient, piezoelectric, vibrational), only a few are capable of providing the continuous power required to operate a single sensor (Lajnef et al. 2008).

There are research projects currently exploring the possibilities of using nuclear energy in the form of a micro battery. These batteries would be able to last for long periods of time, which would minimize the need to replace batteries for active sensors. The micro size of the battery would also allow a significant size reduction for active sensors.

This technology is still in the beginning phases and it will be a few years until any prototypes are available. One challenge researchers already face is keeping the cost of these nuclear batteries affordable. The cost increases with the number of radioisotopes used (Wagner 2007).

A number of other challenges have been identified with respect to the wide-scale implementation of MEMS/nanotechnology in highway engineering (Steyn 2008, Wang and Li 2008):

- **Dimensional chasm:** Considering the large volumes of transportation materials that are being handled at the time of construction, the performance of the nanomaterials and MEMS sensors in combination with bulk aggregates and binders should be evaluated to ensure that their beneficial properties are still harnessed at these scales.

- **Costs:** Currently, the costs of most nanotechnology/MEMS sensors and equipment are relatively high. However, with most novel technologies, the costs are expected to decrease over time, especially as manufacturing technologies improve. Also, as mentioned previously, the MEMS products are custom-designed and application-specific, rather than generic, which requires extensively-funded research programs for development and full-scale evaluation of the products.

- **Environment and health issues:** Leaching of nanomaterials and byproducts of MEMS sensor construction material interactions into groundwater, release of toxic materials into airways through the generation of dust, and exposure to potentially harmful materials during construction and maintenance operations are some potential environmental impacts of using nanomaterials/MEMS that have not yet been researched.

- **Reliability and consistency:** Issues like survivability of sensors and materials for long-term stable operation need to be evaluated. The impacts of embedding the sensor on the performance of a structure and vice versa need to be assessed.

- **Compatibility:** The impacts of embedded MEMS devices on the whole construction process, as well the compatibility of their installation with current construction methods, will determine their widespread acceptance for health monitoring of transportation infrastructure systems.

LABORATORY (AND FIELD) TESTING OF CONCRETE-EMBEDDED SENSORS (TASK 2)

Selection of MEMS Sensors

The suppliers or inventors of the passive systems reviewed here were contacted to obtain MEMS sensors for use in this research. Of the passive systems, the only readily-available systems are the WAKE, Inc. HardTrack Concrete Monitoring System and the Sensirion Inc. USA Digital Humidity MEMS Sensor. Other passive systems are either still under development or are proprietary (the ADC MEMS Concrete Monitoring System, JHUAPL WESP system, etc.) or no future developments have been reported (Smart Pebbles, Hygrometrix, etc.).

The main active systems are Crossbow's wireless sensor network and Sensicast's SensiNet. Both of these active systems are commercially available, but they were not considered for use in this project because the sensor dimensions are large, not embeddable in concrete, and no microprocessor within the sensor. The WAKE HardTrack Concrete Monitoring System and the Sensirion Digital Humidity Sensor were selected for this study and are briefly reviewed below. As a reference MEMS sensor, the Thermochron iButtons from Maxim Integrated Products were also used.

WAKE HardTrack Concrete Monitoring System

The HardTrack Concrete Monitoring System from WAKE uses RFID technology to gather temperature data of in-situ concrete in a very efficient and cost effective method. The system consists of a RFID transponder called an i-Q32T tag (by IDENTEC SOLUTIONS) and a portable transceiver called a Pro (WAKE, Inc. 2010).

The i-Q32T tag has the capability to capture the ambient temperature of the concrete it is buried in and to communicate the information to the portable Pro. The i-Q32T, as shown in Figure 22, contains an internal MEMS sensor for temperature monitoring that measures and logs the temperature in definable intervals.

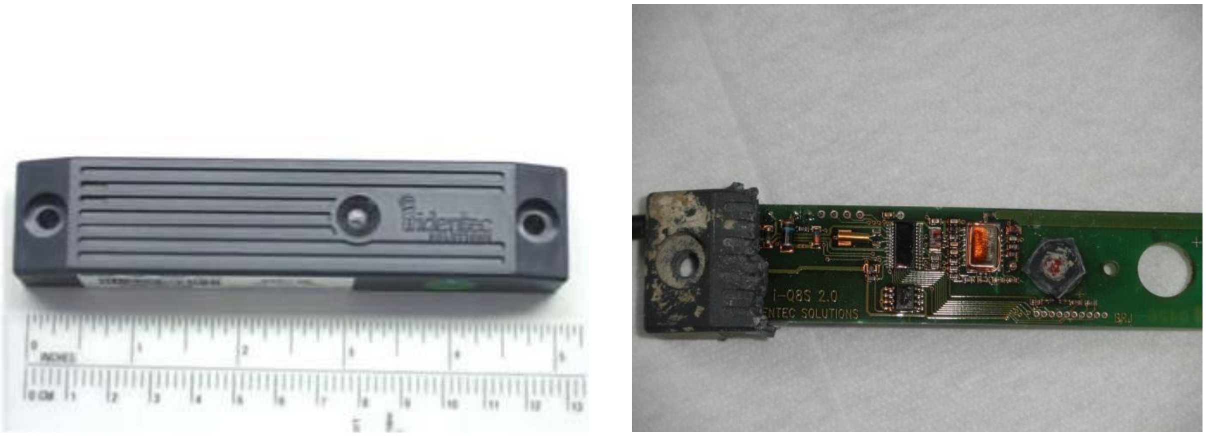


Figure 22. i-Q32T wireless RFID transponder (WAKE, Inc.)

The collected data could be imported into the portable Pro, shown in Figure 23, wirelessly for maturity calculation and saving data to the PC for posterity. The use of two-way RF communication between the buried tag and a handheld PC enables the PC to read and write data to the RFID tag. The brand new i-Q350 series of RFID tags by IDENTEC SOLUTIONS provide an even larger communication range of up to 500 m.

Figure 23. HardTrack Portable Pro (WAKE, Inc.)

WAKE, Inc. loaned one of their HardTrack concrete monitoring systems for evaluation purposes in this research.

Some advantages in using the WAKE HardTrack Concrete Monitoring System to determine optimum concrete strength, curing rates, and documented quality control data for a new concrete project, as reported by the manufacturer (at www.wakeinc.com) include:

- Accelerated opening times.
- Early formwork removal.
- Guesswork and dependence upon cylinders is no longer required.
- Accelerated pre-stressed release times.
- Determination of sawing times for joints. The contractor can optimize time and equipment wear by sawing when the concrete is strong enough, but not too strong.
- The in situ readings from RFID tags give the true temperatures of the concrete at that location rather than relying on the conditions of the concrete in a cylinder. Strength is known at several locations by inspecting temperature sensors at several locations, especially the critical areas. As a result, the weaker locations in the concrete will be known.
- Raw temperature data is available at all times during the hydration process. This gives an opportunity to contractors to know if the concrete is hydrating at a rate that is too fast, or at a temperature too high or low. This real-time information at several locations allows the contractor to take corrective action.

Sensirion Digital Humidity Sensor

Sensirion, Inc. has developed a pin type of relative temperature and humidity sensor (SHT 7x series), combined with the analog and digital signal processing circuitry, on a tiny silicon chip by means of MEMS technology, as shown in Figure 24.

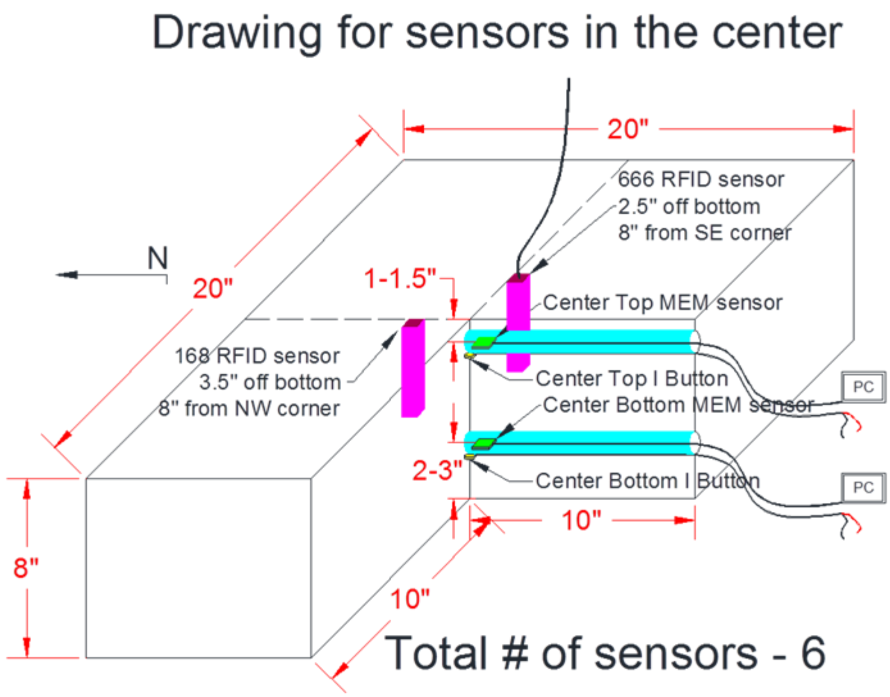
Figure 24. SHT75 Sensirion digital temperature and humidity sensor (Sensirion, Inc. 2010)

The humidity sensor element is built out of a capacitor consisting of a pair of conductors separated by a dielectric (Sensirion, Inc. 2010). The dielectric of polymer absorbs or releases water proportional to the relative environmental humidity, and thus changes the capacitance of the capacitor. This change in capacitance can be measured by an electronic circuit, which allows the relative air humidity to be determined.

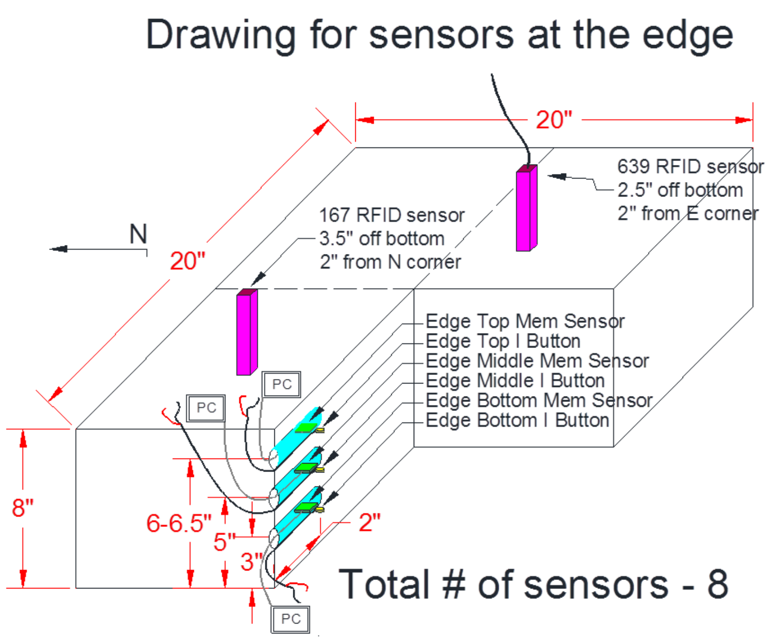
A micro-machined finger electrode system with different protective and polymer cover layers forms the capacitance for the sensor chip, and, in addition to providing the sensor property, simultaneously protects the sensor from interference. Figure 24 presents the SHT75 digital temperature and humidity sensor that was evaluated in this research.

PCC Slab Instrumentation

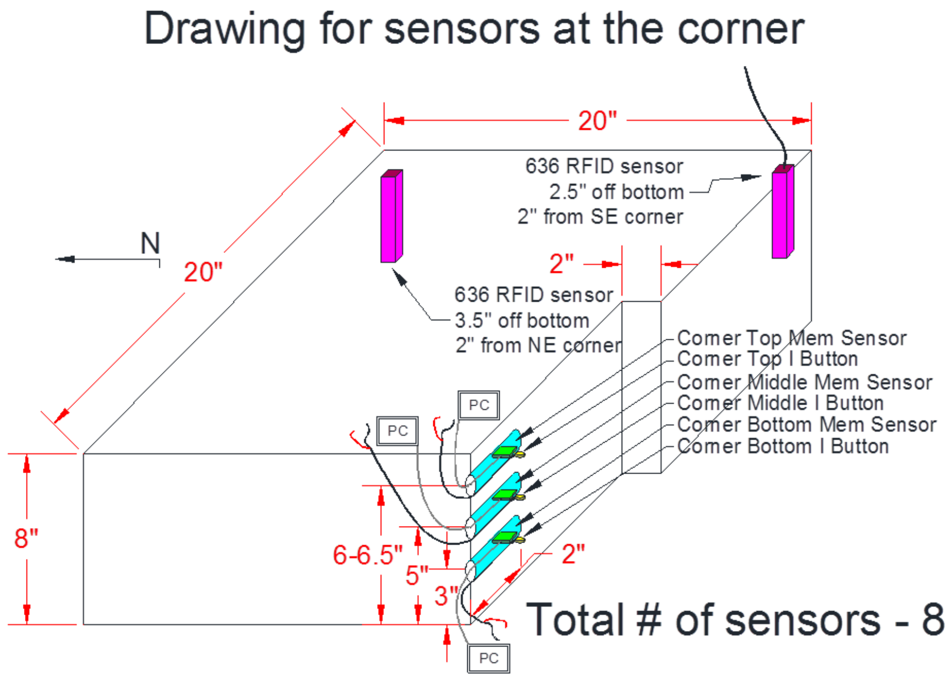
A concrete slab form was fabricated to install the selected MEMS sensors. Non-wireless (wired) Thermochron iButtons from Maxim were also installed as reference MEMS sensors for temperature measurements. The design dimensions of the concrete slab were 20×20×8 in. A total of 19 of sensors were installed at three different locations of the slab (center, edge, and corner of slab). Figure 25 illustrates the layout of sensor installations within the formwork before the pouring of concrete.


Drawing for sensors in the center
20"
666 RFID sensor
2.5" off bottom
8" from SE corner
N
20"
1-1.5"
Center Top MEM sensor
168 RFID sensor
3.5" off bottom
8" from NW corner
Center Top I Button
Center Bottom MEM sensor
PC
2-3"
Center Bottom I Button
PC
10"
8"
10"
Total # of sensors - 6

(a)


Drawing for sensors at the edge
20"
639 RFID sensor
2.5" off bottom
2" from E corner
167 RFID sensor
3.5" off bottom
2" from N corner
N
20"
Edge Top Mem Sensor
Edge Top I Button
Edge Middle Mem Sensor
Edge Middle I Button
Edge Bottom Mem Sensor
Edge Bottom I Button
PC
PC
8"
6-6.5"
5"
3"
2"
PC
Total # of sensors - 8

(b)



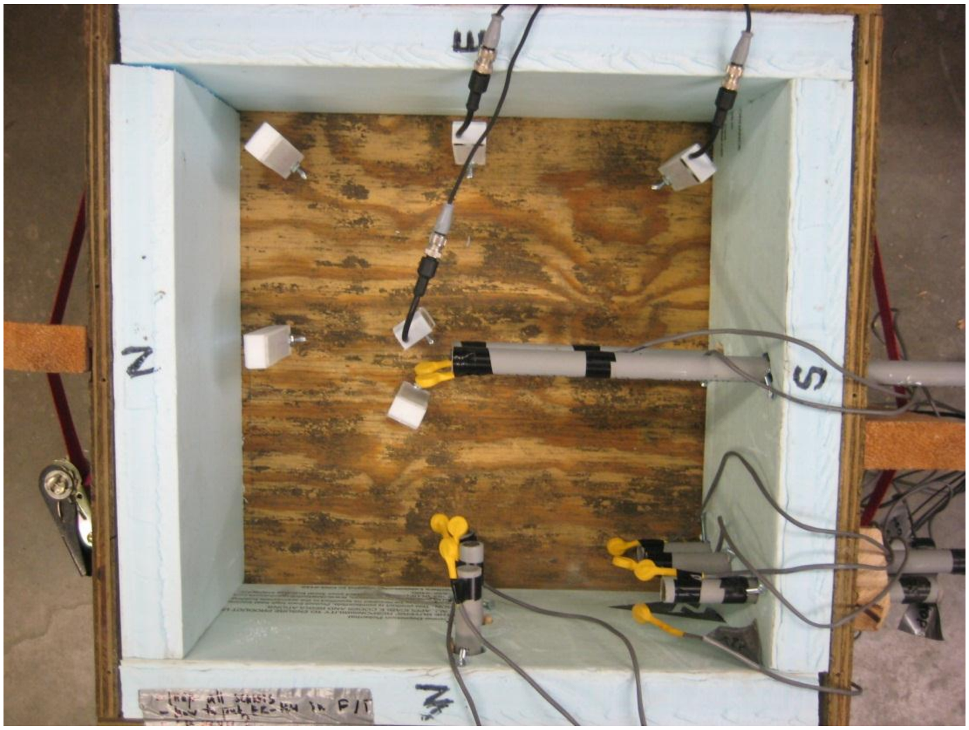
(c)

Figure 25. Lay out of sensor installations: (a) center, (b) edge, (c) corner

A concrete form was custom fabricated with holes to accommodate the sensor installation (see Figure 26). A total of five sensors were located right at the center of the slab: two iButtons at the top and bottom of the slab, two Sensirion sensors at the top and bottom of the slab, and one wireless RFID sensor in the middle.

Figure 26. MEMS sensor installation in concrete slab form

Seven sensors were installed in the slab corner: an iButton and a Sensirion sensor at the top, middle, and bottom of the slab and one wireless RFID sensor in the middle. Likewise, seven sensors were installed along the slab edge with the same configuration. Figure 27 illustrates the concrete slab form with the sensor installations.



(a)

(b)

Figure 27. Instrumented concrete form: (a) plan view, (b) installed sensor types

After the sensors were installed in the concrete form, concrete mix was prepared following a typical Iowa concrete pavement mix specification:

- Water-to-cement ratio: 0.45
- Cement: 530 pounds per cubic yard
- Fly ash: 95 pounds per cubic yard
- Fine and coarse aggregates: 2,900 pounds per cubic yard

Figure 28. Preparation of concrete mix

The following are the fresh concrete properties after mixing:

- Slump: 4 in. (see Figure 29)
- Air content: 1.8 percent
- Unit weight: 150 pounds per cubic foot

The mixed fresh concrete was carefully placed in the instrumented concrete form (see Figure 30). Figure 31 shows the instrumented concrete form after the placement of fresh concrete. Figure 32 shows the PCC cylinders that were prepared for compressive strength testing.

Figure 29. Slump test

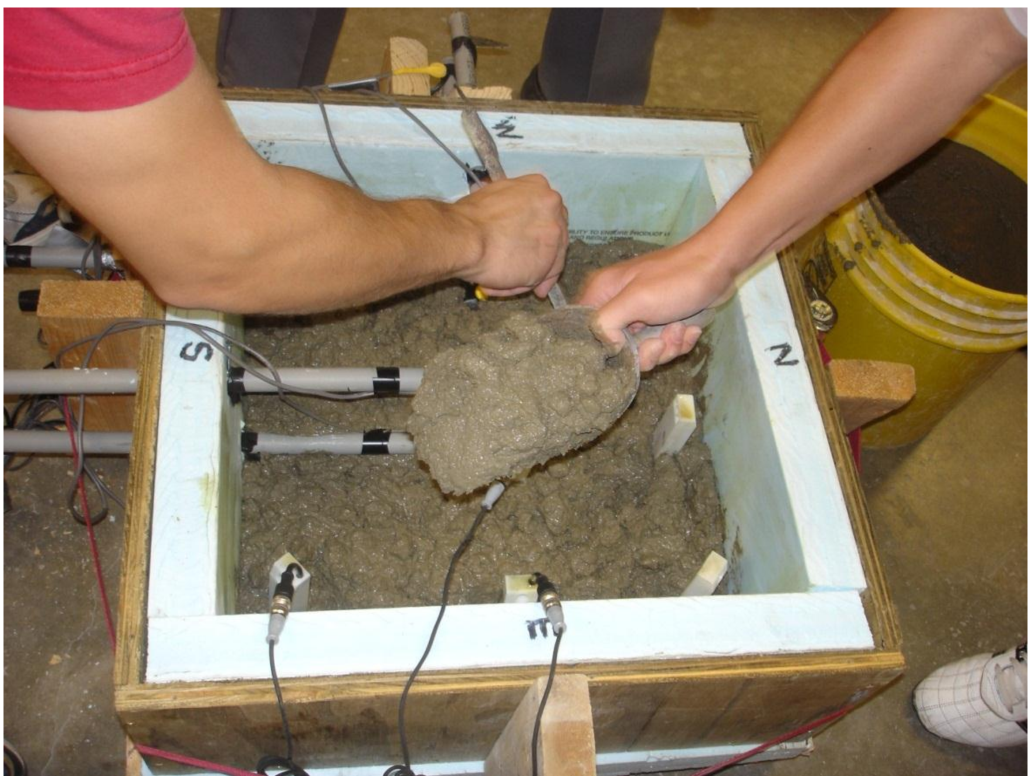


Figure 30. Placement of fresh concrete in the instrumented concrete form

Figure 31. Freshly placed concrete in the instrumented form

Figure 32. Preparation of PCC cylinders for compressive strength testing

Data Acquisition System

The data acquisition system, as shown in Figure 33, consists of the data readers for sensors and a laptop computer. The data readers for wireless RFID and the Sensirion sensors include the portable Pro and the EK-H4 evaluation kit, respectively. Both readers can interface with the laptop computer through a USB port. Temperature and humidity data were acquired from the MEMS sensors in accordance with the experimental test program described in the next section.

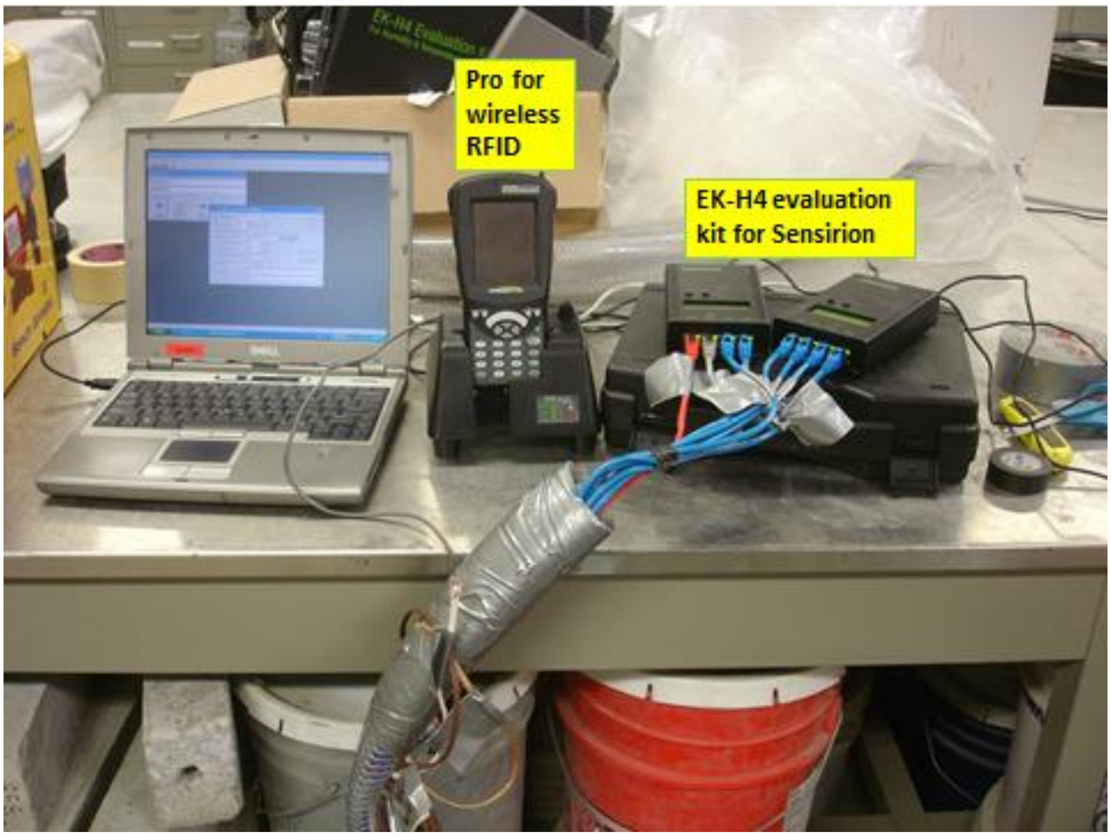


Figure 33. Data acquisition system

Experimental Test Program

The experimental test program in this study consisted of four test phases based on different test conditions. Table 1 summarizes the experimental test program designed to investigate the feasibility of MEMS sensors for continuous monitoring of concrete pavements.

Table 1. Summary of experimental test program

Test Phase	Period	Location	Note
1	10/07/2010 – 10/12/2010	ISU PCC laboratory	- Room temperature conditions - Cement hydration in concrete
2	10/19/2010 – 10/24/2010	Freezing and thawing room	- Five rapid freeze-thaw cycles - Each freeze-thaw cycle lasting a day with temperatures ranging from 0ºF to 50ºF
3	10/26/2010 – 11/01/2010	Freezing and thawing room	- One slow freeze-thaw cycle - Freeze-thaw cycle lasting six days with temperatures ranging from 0ºF to 70ºF
4	11/13/2010 – 04/23/2011	Driveway in Ames, Iowa	- Actual Iowa road conditions - Air temperatures ranging from 0ºF to 80ºF

During the first test phase, the installed sensors measured the temperature variations inside the slab produced by generation of heat during cement hydration. The temperature data collected during this phase was also used to estimate the extent of hydration and PCC strength gain through the maturity concept, as will be discussed later.

During test phases 2 and 3, the instrumented slab was placed in a freezing and thawing room at the ISU PCC laboratory. The second test phase involved five rapid freezing and thawing cycles. Each cycle lasted about a day (24 hours) and the temperature variation of each cycle ranged from 0ºF to 50ºF. The test phase 3 adopted one cycle of slow freezing and thawing condition. The duration of the one cycle was about six days and the temperature variation ranged from 0ºF to 70 ºF.

In the fourth experimental test phase, the MEMS sensor measurement capacity in actual field/in situ conditions was evaluated by burying the instrumented slab underground near a driveway in Ames, Iowa.

The sensor measurement data were collected at the end of each test phase.

Laboratory and Field Test Results

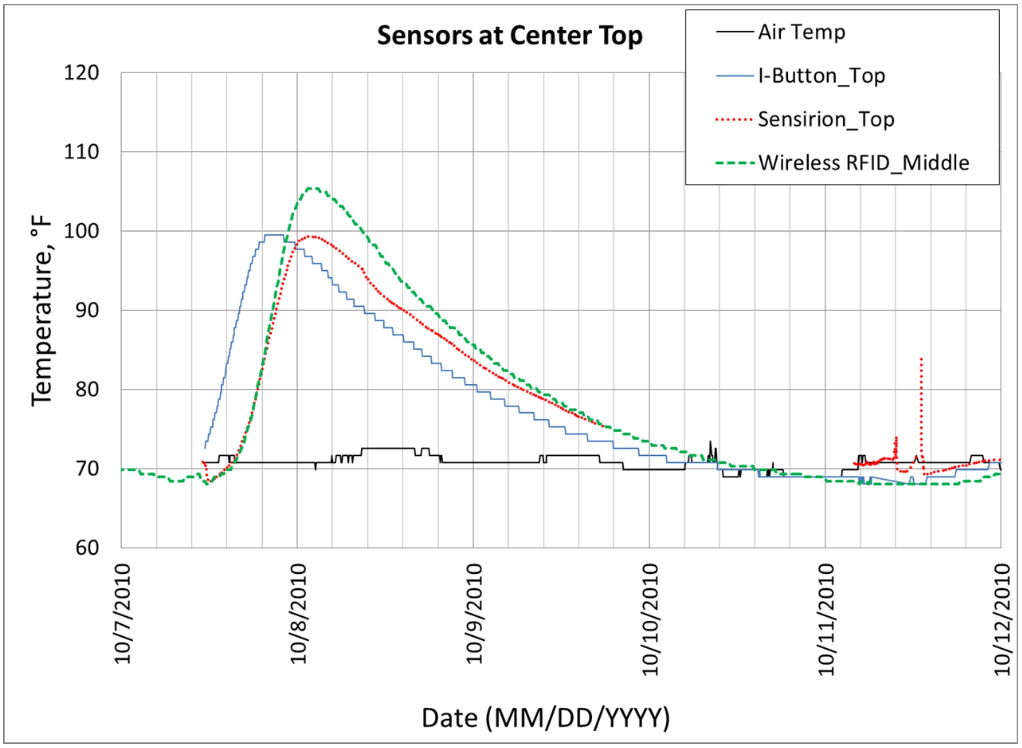
Phase 1 Test Results

Figure 34 shows the instrumented slab in the ISU PCC laboratory during the first test phase.

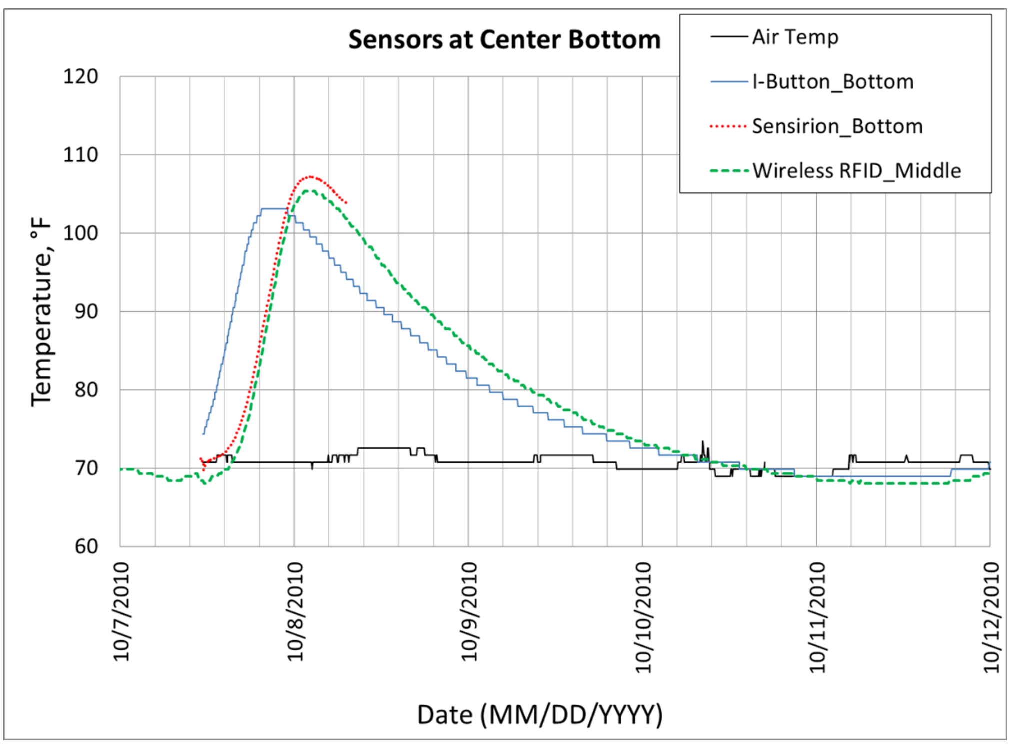
Figure 34. Instrumented slab in ISU PCC laboratory during test phase 1

Temperature measurements from sensors are presented in Figure 35 through Figure 37.

Figure 35 shows temperature measurements of sensors at the slab center. All installed sensors were able to capture the heat of cement hydration behavior in concrete during the first three days after the fresh concrete was placed. However, the Sensirion sensors were not always functional. In comparison to iButtons as the reference wired sensor, the wireless RFID sensors send measurement signals about five hours later. Similar findings can be observed in Figure 36 for the edge-of-slab sensors and Figure 37 for the corner-of-slab sensors.

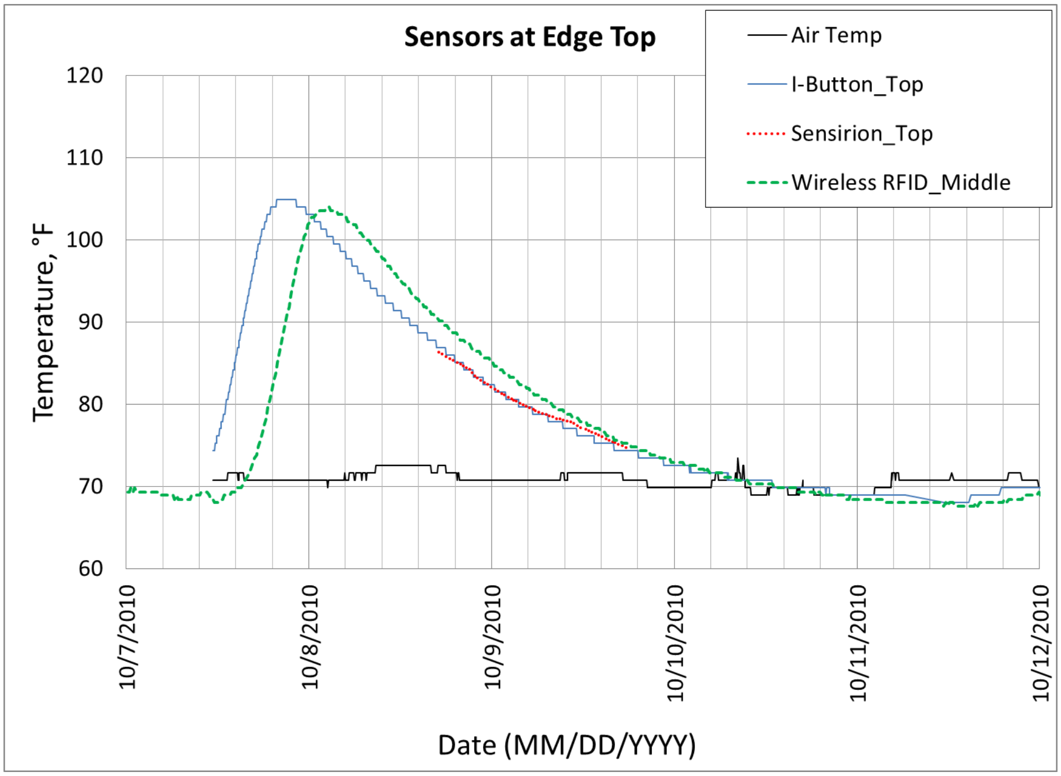


(a)

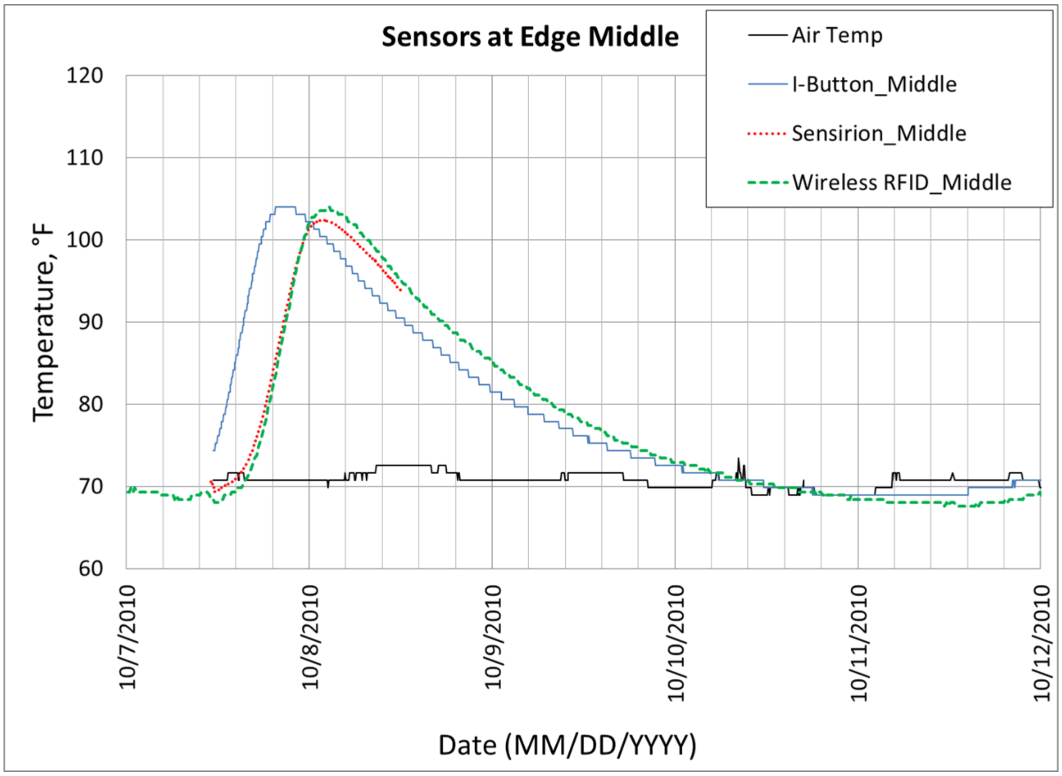


(b)

Figure 35. Temperature measurements from MEMS sensors at slab center during test phase 1: (a) top, (b) bottom


Sensors at Edge Top
Air Temp
I-Button_Top
Sensirion_Top
Wireless RFID_Middle
120
110
100
90
80
70
60
Temperature, °F
10/7/2010
10/8/2010
10/9/2010
10/10/2010
10/11/2010
10/12/2010
Date (MM/DD/YYYY)

(a)


Sensors at Edge Middle
Air Temp
I-Button_Middle
Sensirion_Middle
Wireless RFID_Middle
120
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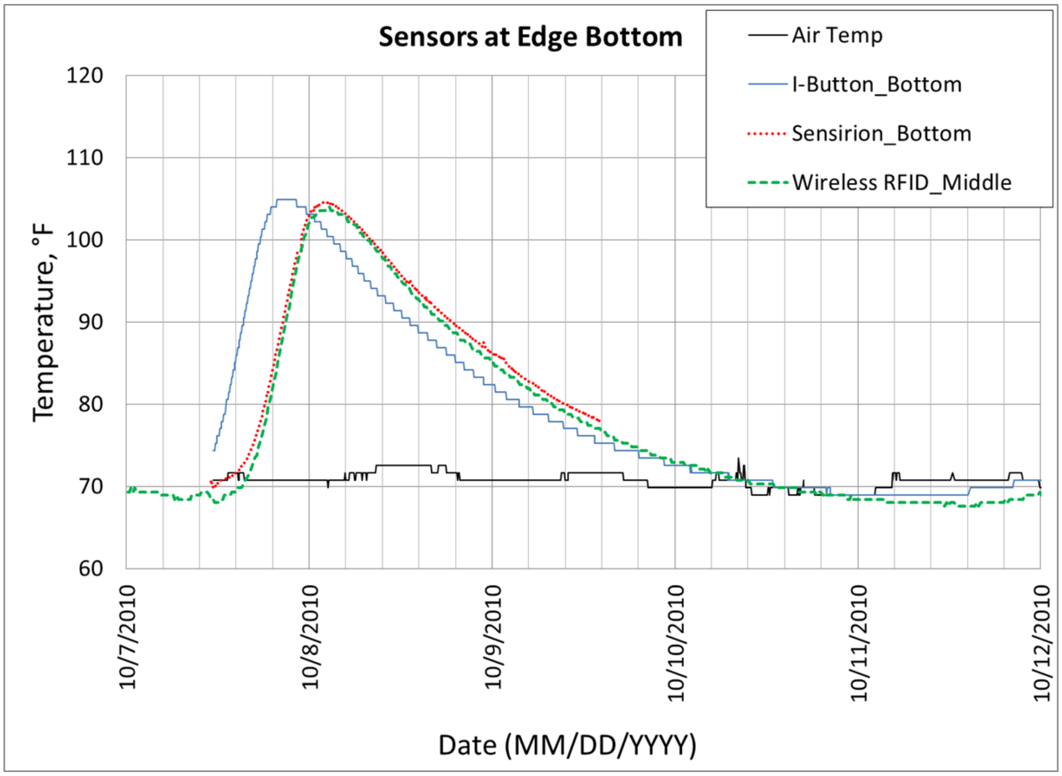
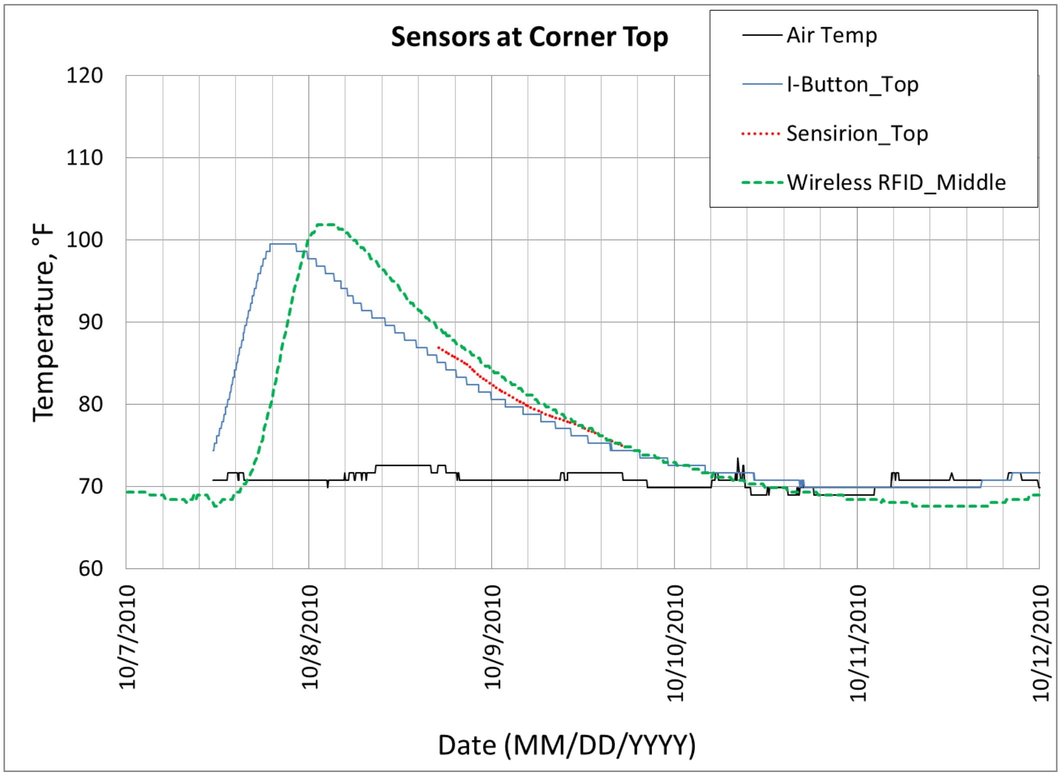
Temperature, °F
10/7/2010
10/8/2010
10/9/2010
10/10/2010
10/11/2010
10/12/2010
Date (MM/DD/YYYY)

(b)

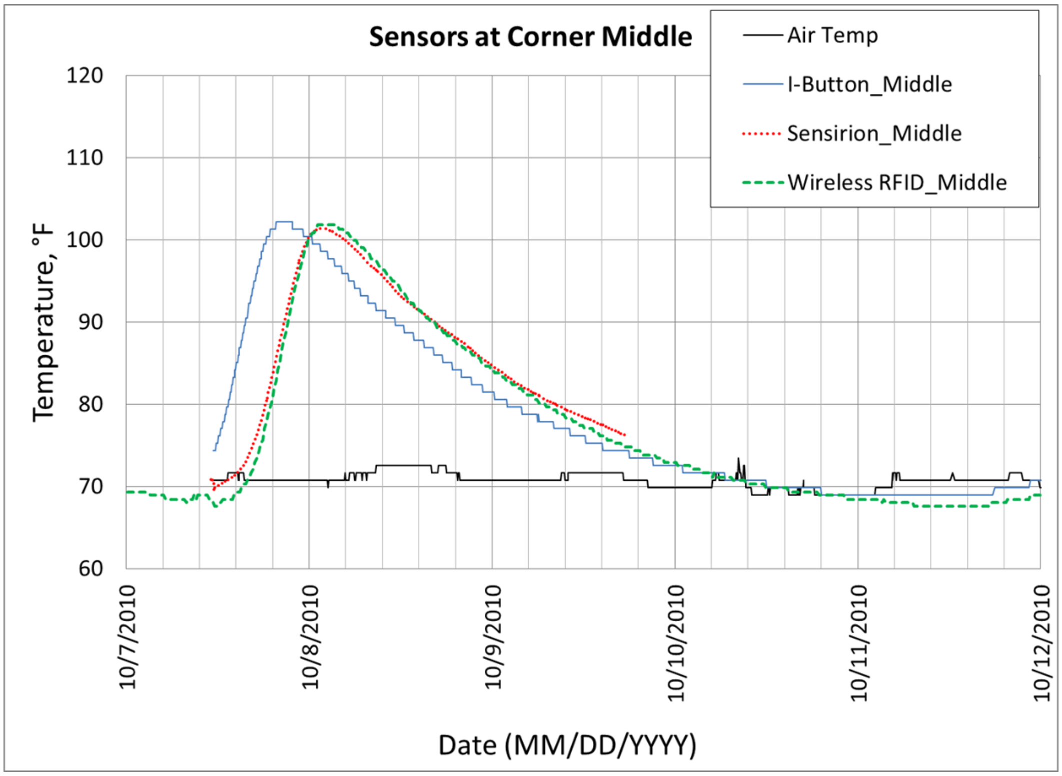


(c)

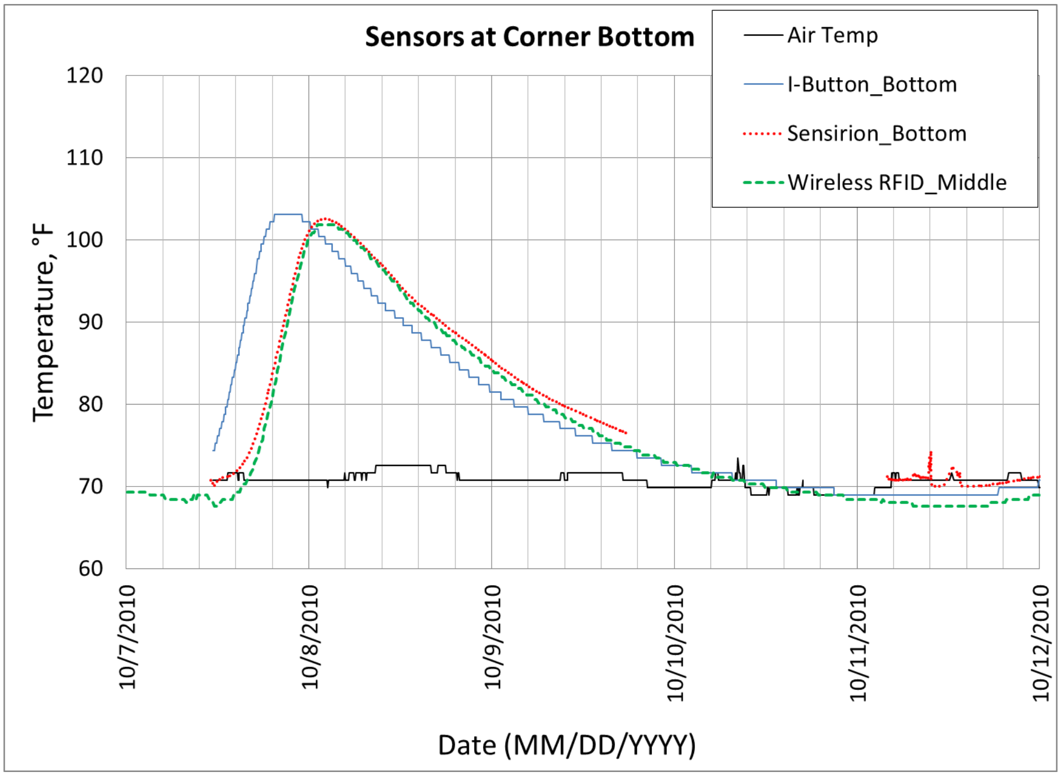
Figure 36. Temperature measurements from MEMS sensors at slab edge during test phase 1: (a) top, (b) middle, (c) bottom


Sensors at Corner Top
Air Temp
I-Button_Top
Sensirion_Top
Wireless RFID_Middle
Temperature, °F
120
110
100
90
80
70
60
10/7/2010
10/8/2010
10/9/2010
10/10/2010
10/11/2010
10/12/2010
Date (MM/DD/YYYY)

(a)


Sensors at Corner Middle
Air Temp
I-Button_Middle
Sensirion_Middle
Wireless RFID_Middle
Temperature, °F
120
110
100
90
80
70
60
10/7/2010
10/8/2010
10/9/2010
10/10/2010
10/11/2010
10/12/2010
Date (MM/DD/YYYY)

(b)



(c)

Figure 37. Temperature measurements from MEMS sensors at slab corner during test phase 1: (a) top, (b) middle, (c) bottom

Phase 2 Test Results

Figure 38 shows the instrumented slab in the freeze-thaw room during test phases 2 and 3.

Temperature measurements from iButton sensors and wireless RFID tags are presented in Figure 39 through Figure 41. Figure 39 illustrates temperature measurements of sensors at the slab center.

Through these series of tests, the capability of wireless RFID tags to work properly in high-severity temperature conditions was demonstrated because they provided comparable temperature measurements to iButton sensors.

Although the Sensirion sensors were placed inside the slab, they didn't function properly for some reason. Similar findings can be observed in Figure 40 for the edge-of-slab sensors and Figure 41 for the corner-of-slab sensors.

Figure 38. Instrumented slab in freezing and thawing room during test phases 2 and 3

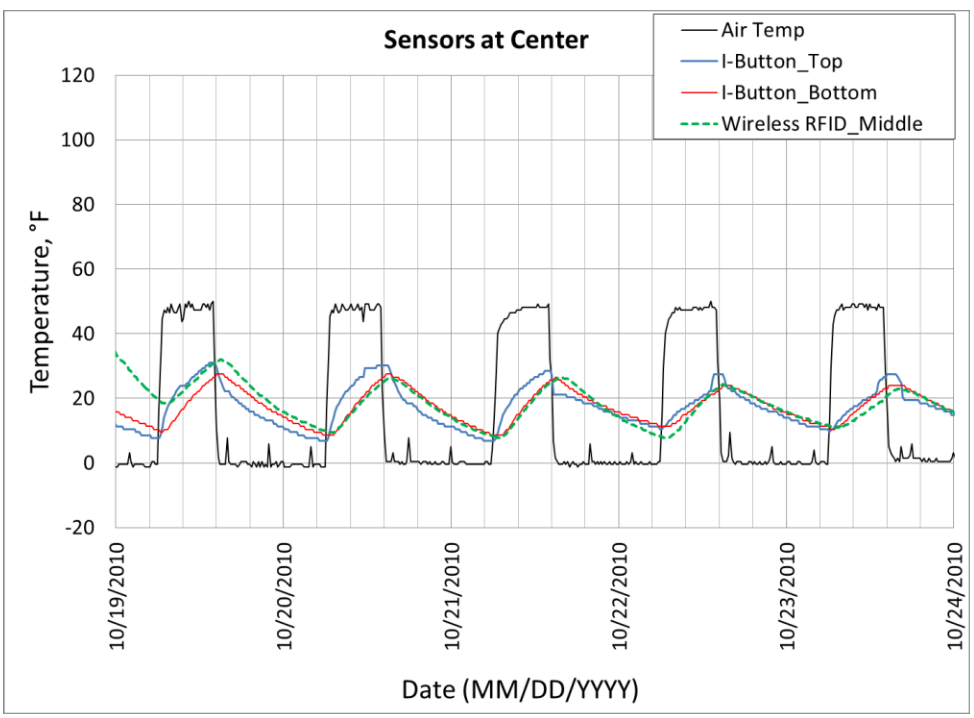


Figure 39. Temperature measurements from MEMS sensors at slab center during test phase 2

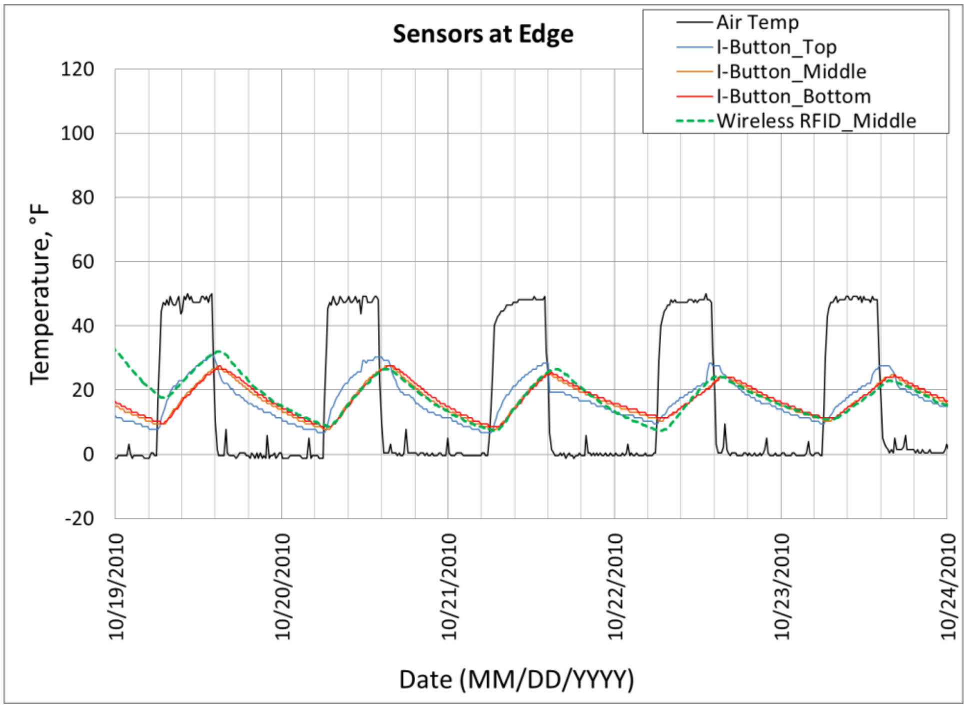


Figure 40. Temperature measurements from MEMS sensors at slab edge during test phase 2

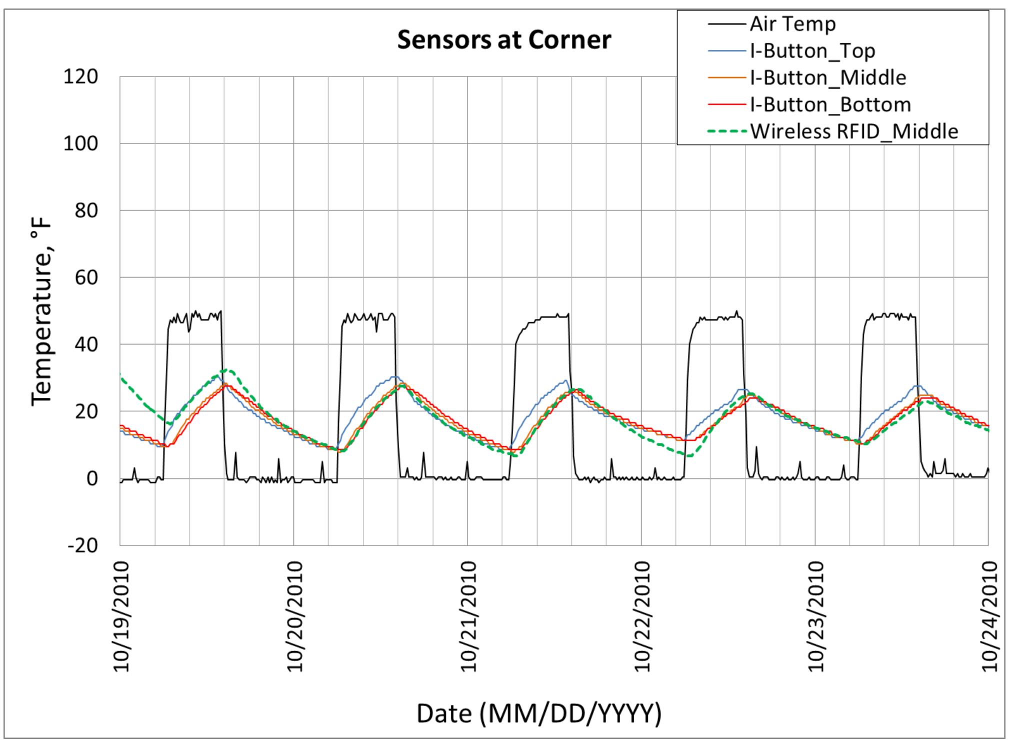


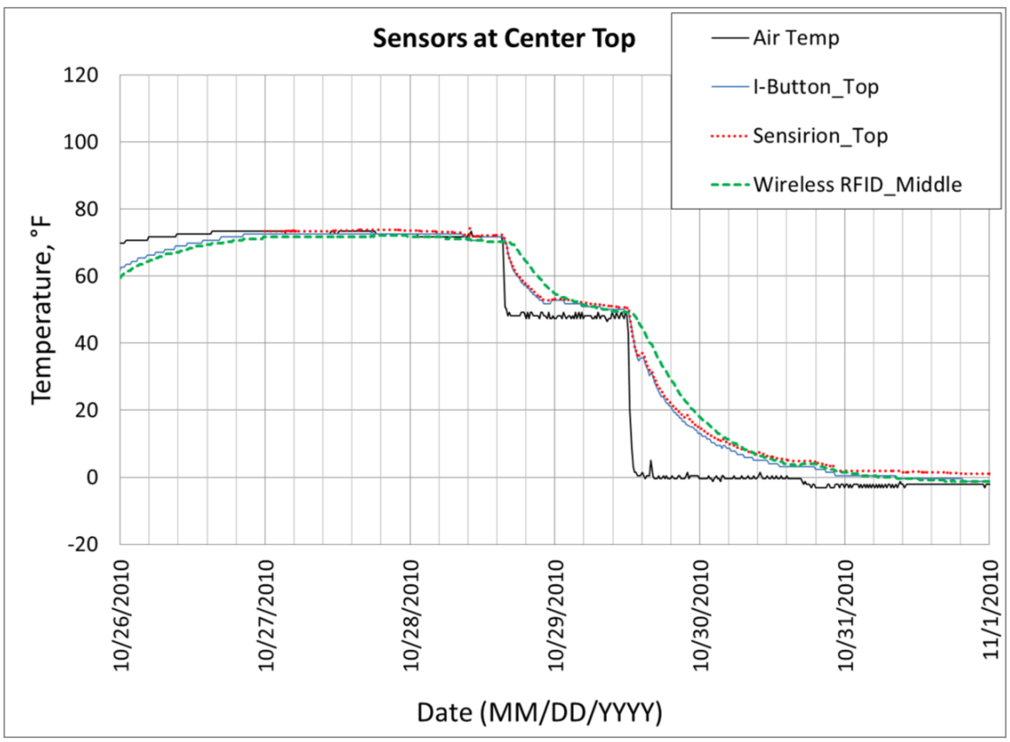
Figure 41. Temperature measurements from MEMS sensors at slab corner during test phase 2

Phase 3 Test Results

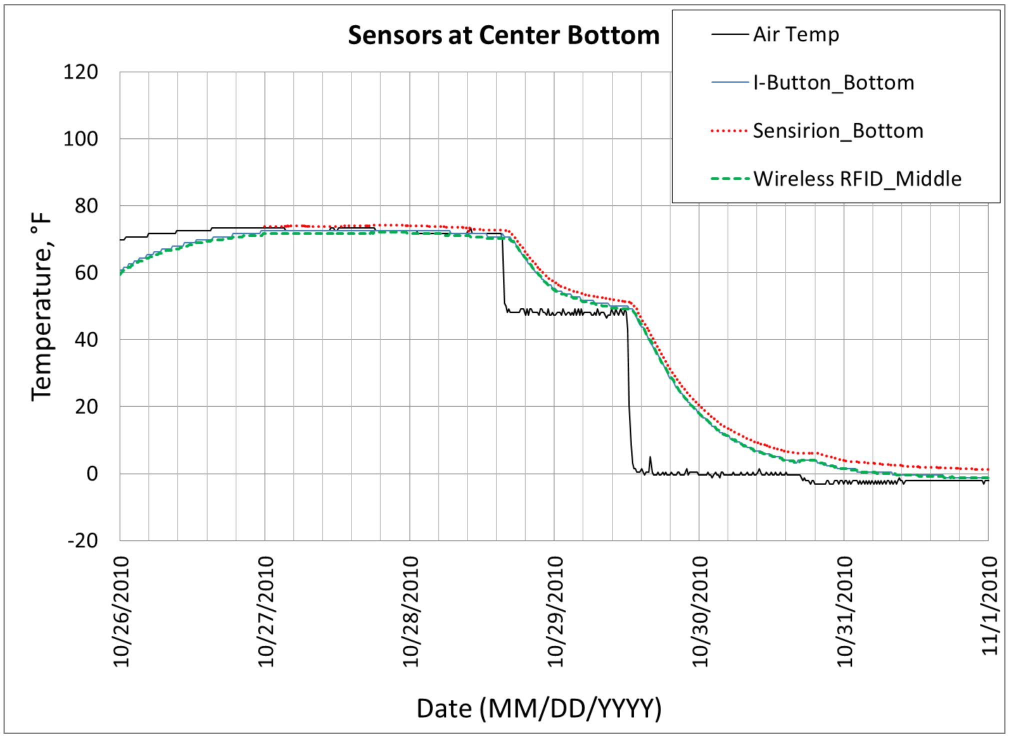
Test phase 3 adopted slow freezing and thawing conditions (while the second test phase adopted rapid freezing and thawing conditions). Temperature measurements from all three types of sensors for test phase 3 are presented in Figure 42 through Figure 44.

Humidity measurements from the Sensirion sensors are presented in Figure 45. The temperature measurements of wireless RFID sensors placed in the slab center are similar to those measured by the wired iButton sensors placed in the middle and bottom of the slab at each location as shown in Figure 43(b) and (c) and Figure 44(b) and (c). Similarly, the temperature measurements of the Sensirion sensors at the corresponding location and depth are similar to those of the wired iButton sensors.

As seen in Figure 45, the Sensirion sensors are able to measure humidity in slow freeze-thaw conditions. These results indicate that the Sensirion sensors can only be utilized in concrete temperature measurements under limited conditions of slow ambient temperature changes.

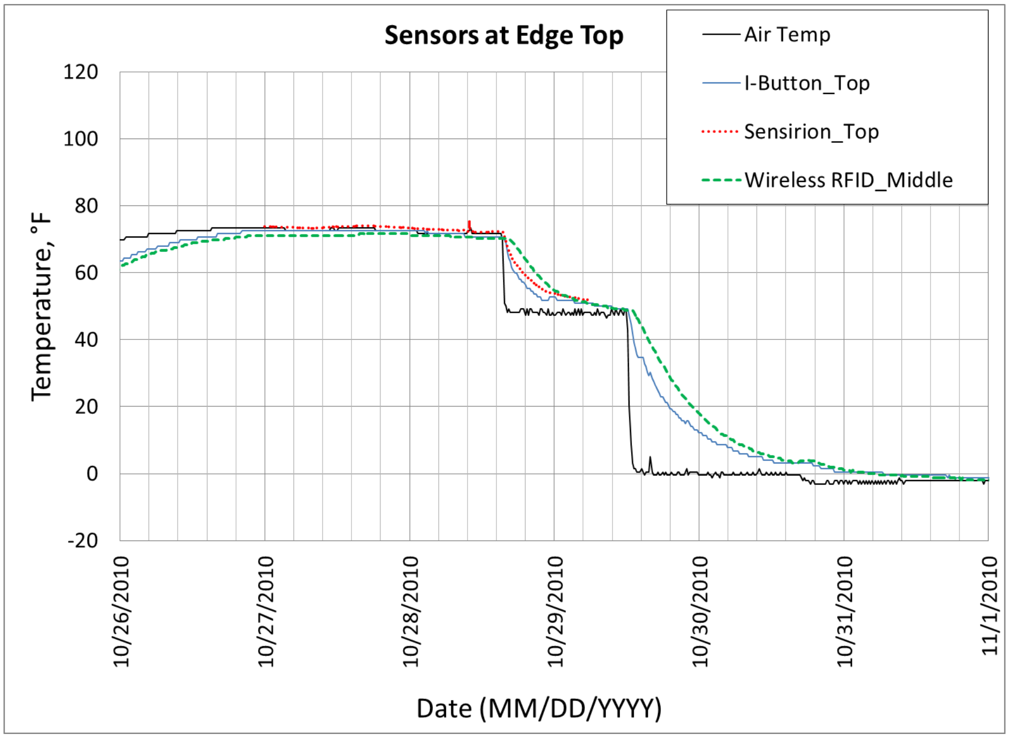


(a)

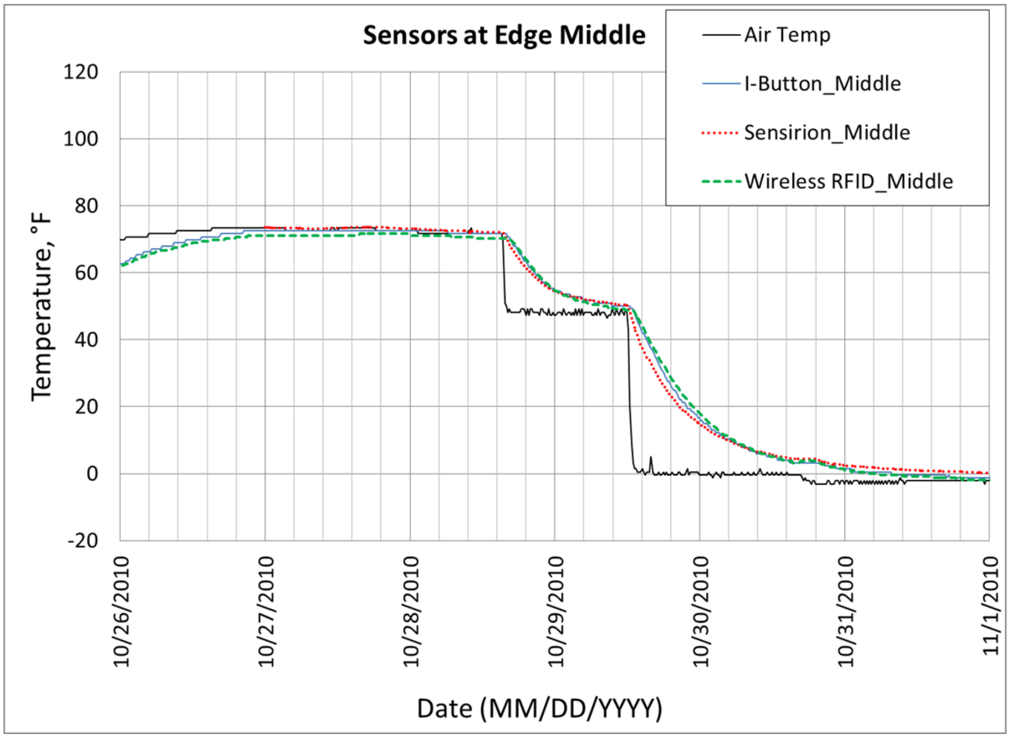


(b)

Figure 42. Temperature measurements from MEMS sensors at slab center during test phase 3: (a) top, (b) bottom


Sensors at Edge Top
Air Temp
I-Button_Top
Sensirion_Top
Wireless RFID_Middle
120
100
80
60
40
20
0
-20
Temperature, °F
10/26/2010
10/27/2010
10/28/2010
10/29/2010
10/30/2010
10/31/2010
11/1/2010
Date (MM/DD/YYYY)

(a)


Sensors at Edge Middle
Air Temp
I-Button_Middle
Sensirion_Middle
Wireless RFID_Middle
120
100
80
60
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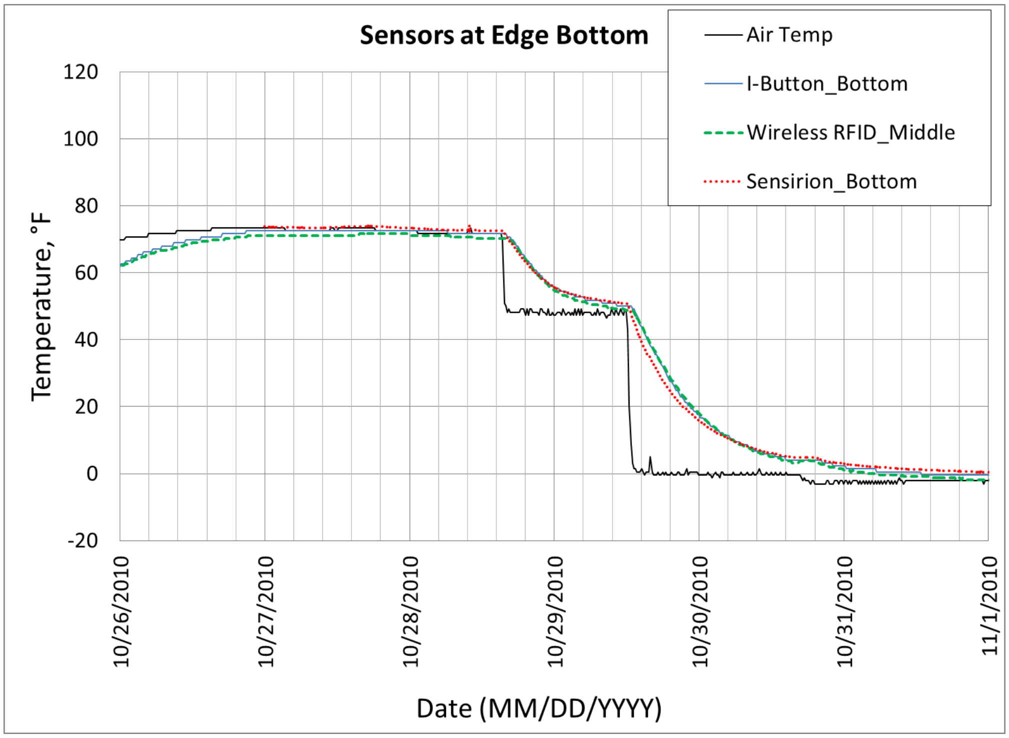
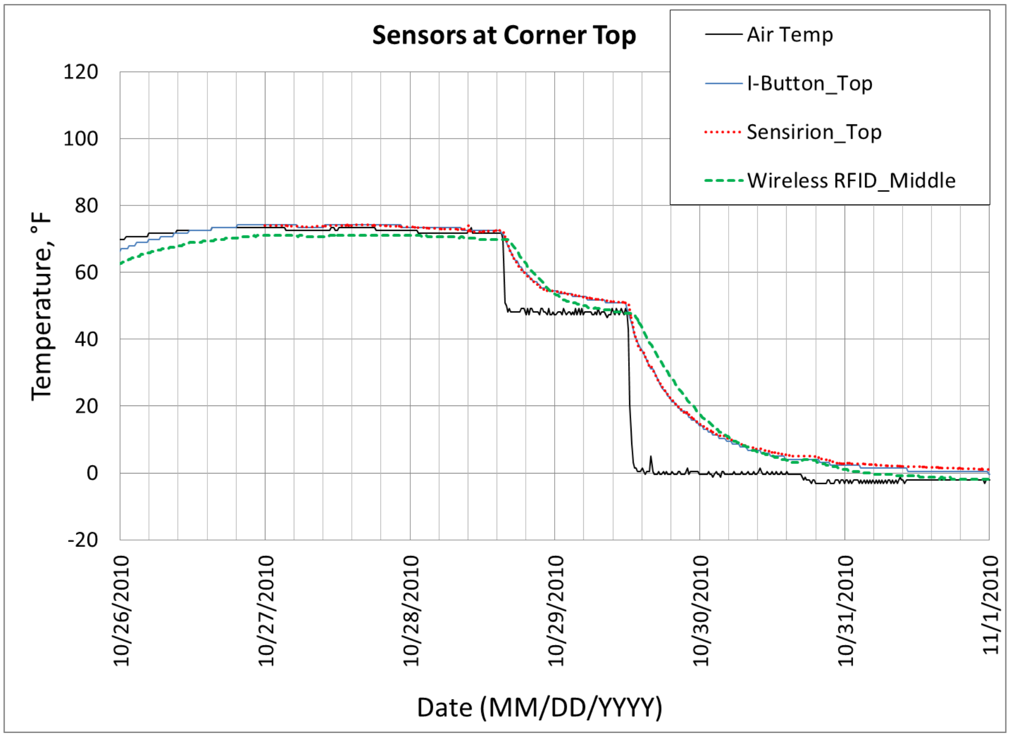
20
0
-20
Temperature, °F
10/26/2010
10/27/2010
10/28/2010
10/29/2010
10/30/2010
10/31/2010
11/1/2010
Date (MM/DD/YYYY)

(b)



(c)

Figure 43. Temperature measurements from MEMS sensors at slab edge during test phase 3: (a) top, (b) middle, (c) bottom


Sensors at Corner Top
Air Temp
I-Button_Top
Sensirion_Top
Wireless RFID_Middle
Temperature, °F
120
100
80
60
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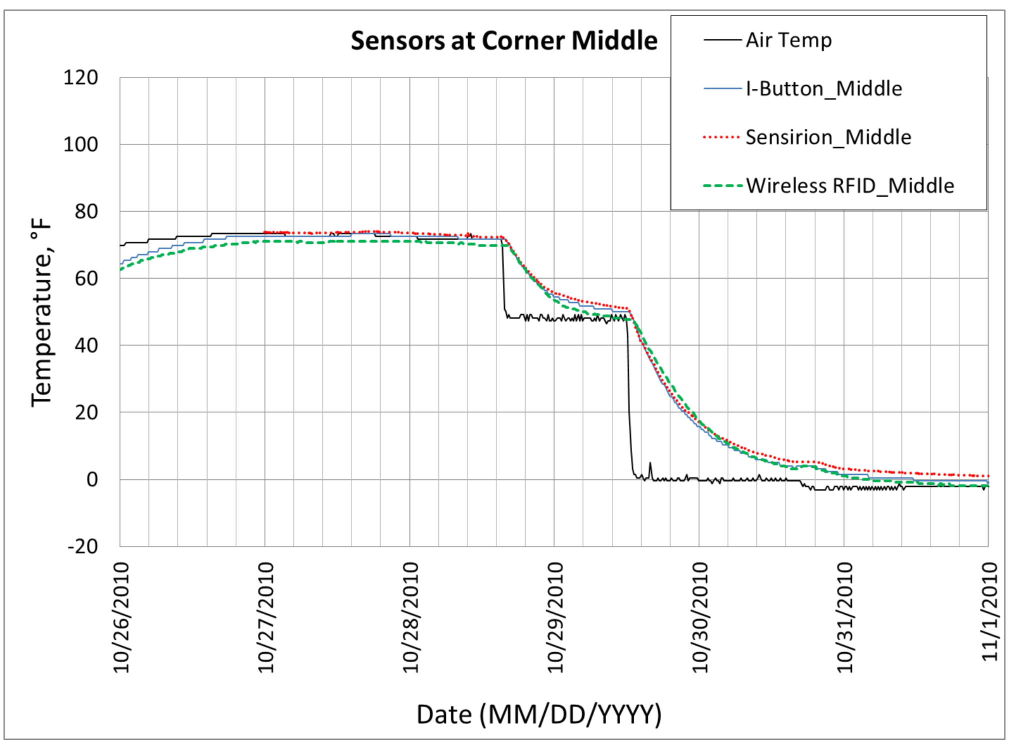
20
0
-20
10/26/2010
10/27/2010
10/28/2010
10/29/2010
10/30/2010
10/31/2010
11/1/2010
Date (MM/DD/YYYY)

(a)


Sensors at Corner Middle
Air Temp
I-Button_Middle
Sensirion_Middle
Wireless RFID_Middle
Temperature, °F
120
100
80
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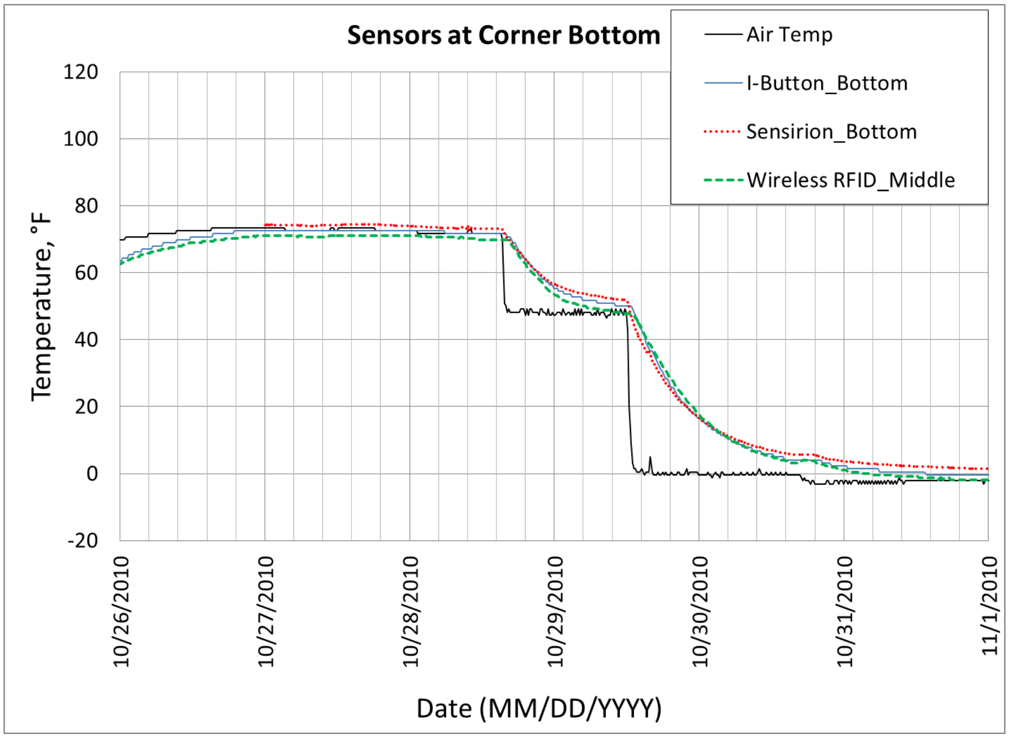
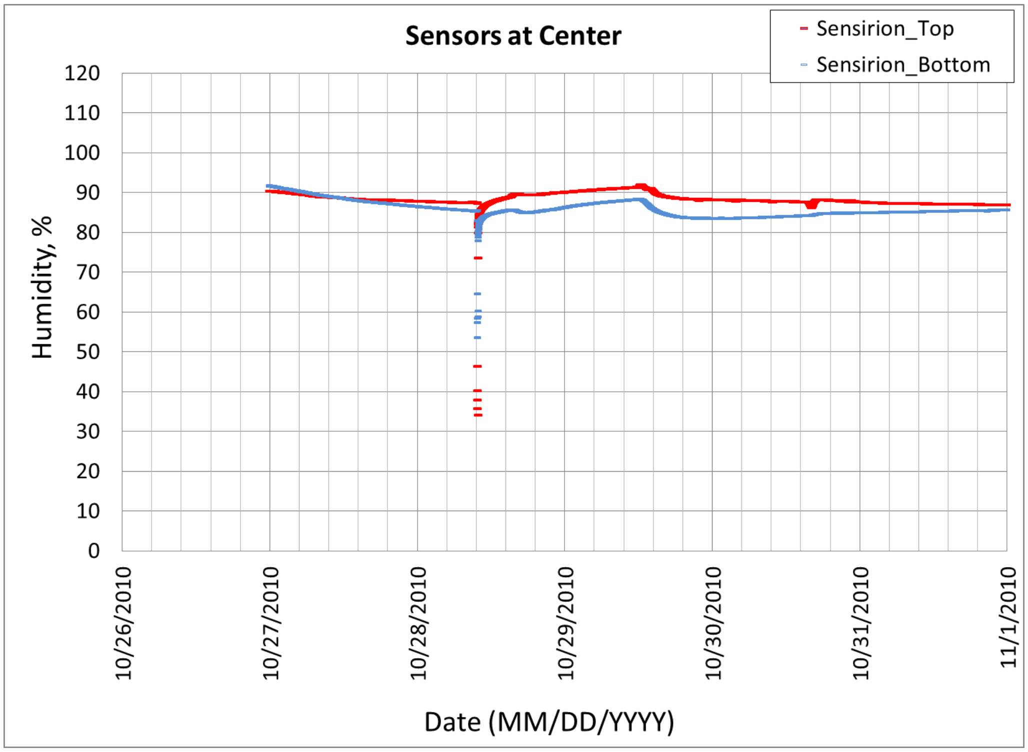
40
20
0
-20
10/26/2010
10/27/2010
10/28/2010
10/29/2010
10/30/2010
10/31/2010
11/1/2010
Date (MM/DD/YYYY)

(b)

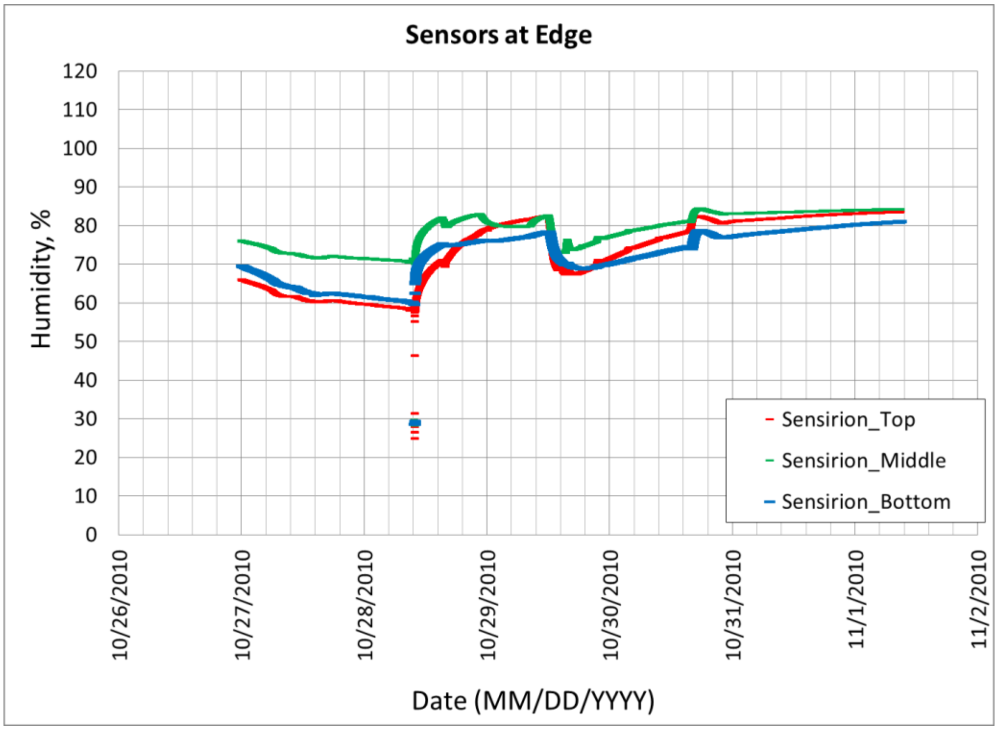


(c)

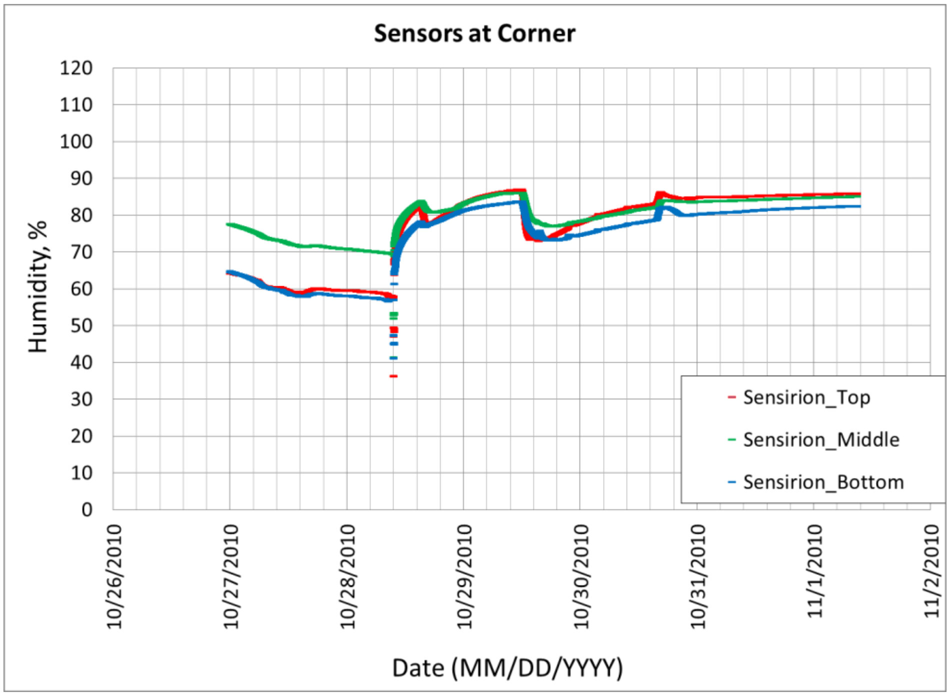
Figure 44. Temperature measurements from MEMS sensors at slab corner during test phase 3: (a) top, (b) middle, (c) bottom


Sensors at Center
Sensirion_Top
Sensirion_Bottom
Humidity, %
120
110
100
90
80
70
60
50
40
30
20
10
0
10/26/2010
10/27/2010
10/28/2010
10/29/2010
10/30/2010
10/31/2010
11/1/2010
Date (MM/DD/YYYY)

(a)


Sensors at Edge
Humidity, %
120
110
100
90
80
70
60
50
40
30
20
10
0
Sensirion_Top
Sensirion_Middle
Sensirion_Bottom
10/26/2010
10/27/2010
10/28/2010
10/29/2010
10/30/2010
10/31/2010
11/1/2010
11/2/2010
Date (MM/DD/YYYY)

(b)



(c)

Figure 45. Humidity measurements from MEMS sensors in slab during test phase 3

Phase 4 Test Results

The fourth test phase focused on evaluation of wireless RFID sensor capacity under actual road climate conditions. The instrumented slab was placed near a driveway in Ames, Iowa as shown in Figure 46.

Figure 47 shows the installation of the wired iButton sensors at the surface. A picture of the buried instrumented slab in freezing weather is captured in Figure 48.

Temperature measurements from wired iButton sensors and wireless RFID tags during test phase 4 are presented in Figure 49 through Figure 51. As seen in these figures, both sensors are capable of measuring in situ temperature variations caused by air temperature variations inside concrete.

Figure 46. Instrumented slab near driveway in Ames, Iowa during test phase 4

Figure 47. Installation of iButton sensors at the surface of the instrumented slab during test phase 4

Figure 48. Buried instrumented slab in severe freezing weather during test phase 4

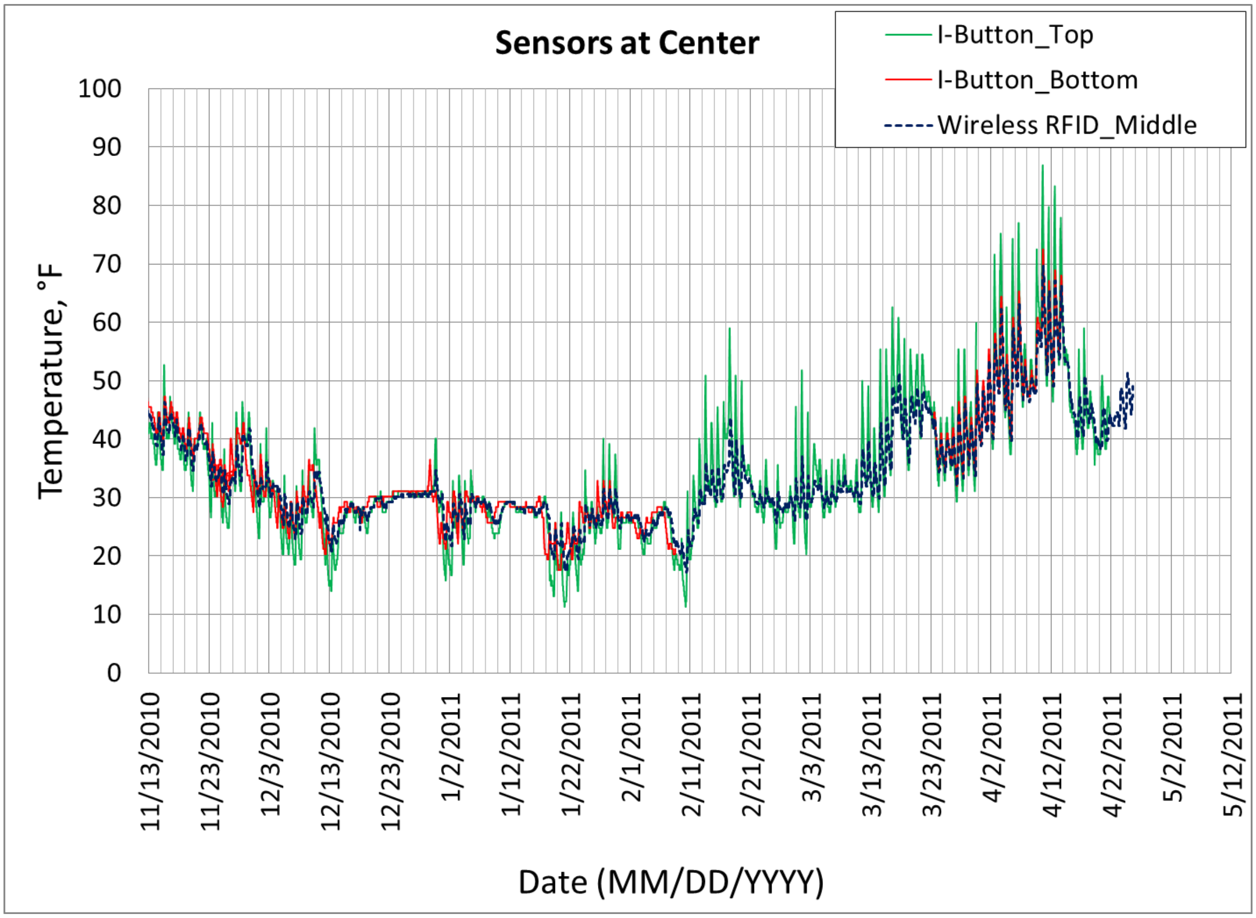


Figure 49. Temperature measurements from MEMS sensors at slab center during test phase 4

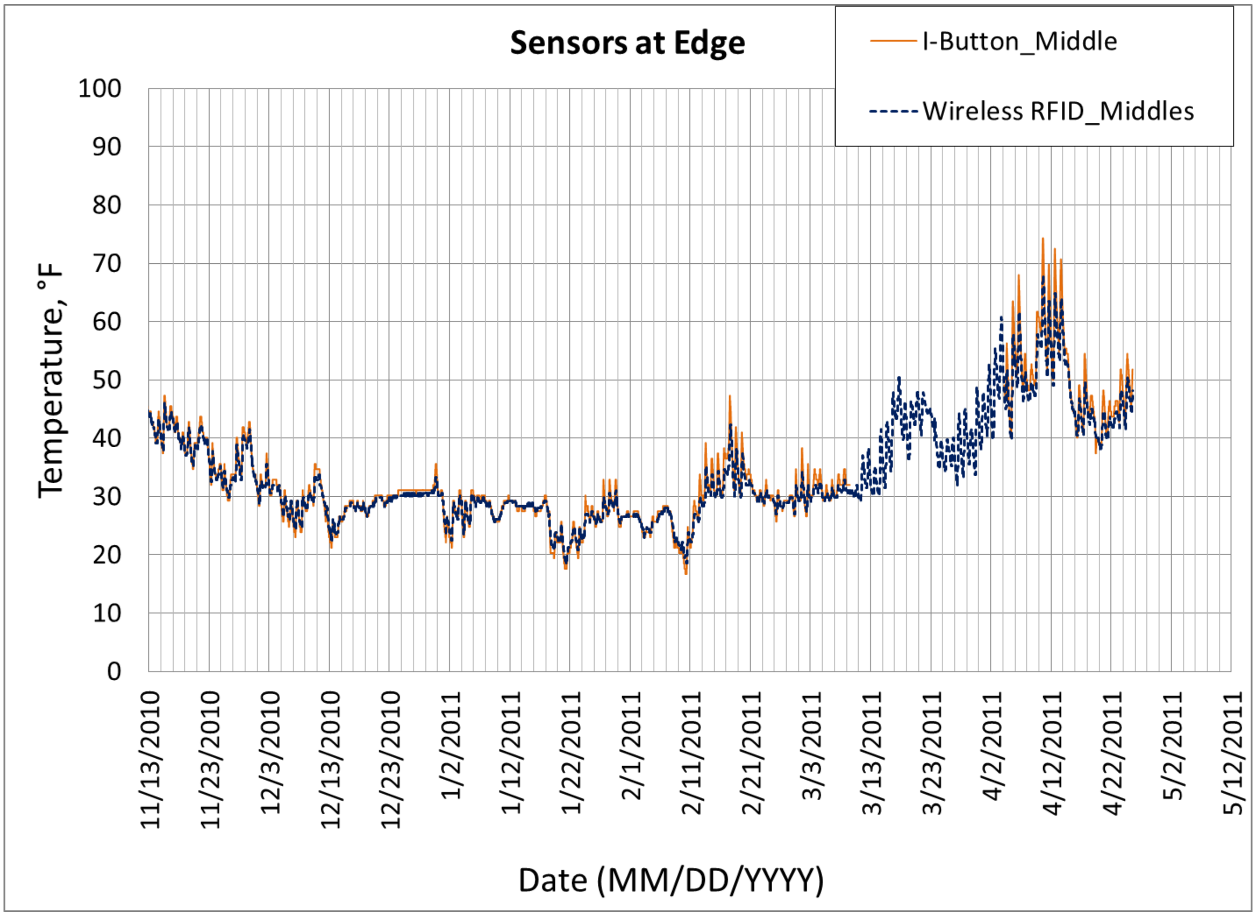


Figure 50. Temperature measurements from MEMS sensors at slab edge during test phase 4

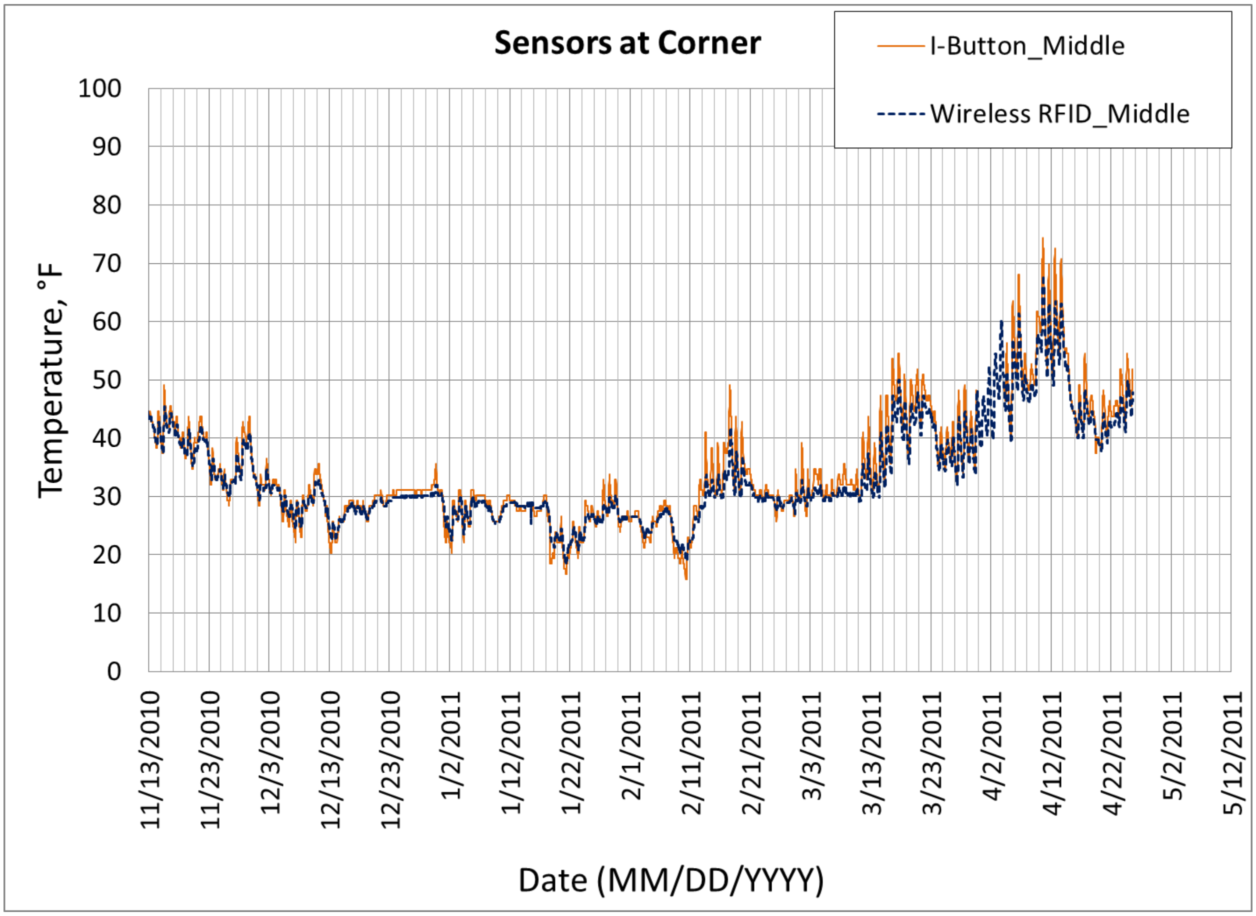


Figure 51. Temperature measurements from MEMS sensors at slab corner during test phase 4

A WIRELESS CONCRETE MONITORING SYSTEM PROPOSED FOR FUTURE RESEARCH (TASK 3)

Based on the completion of tasks 1 and 2 of this research, a conceptual wireless RFID concrete monitoring system is proposed. As noted, the body of knowledge, as well as technology related to RFID, MEMS, and nanotechnology is constantly developing. Many research studies are currently being carried out to investigate the potential application of these technologies for highway infrastructure condition monitoring.

A number of research-scale MEMS sensors and systems have been developed for specific applications. However, reliable off-the-shelf solutions are required by highway agencies for routine highway applications. Therefore, the benefits of the WAKE, Inc. wireless HardTrack Concrete Monitoring System are described here and the system is proposed for future investigation by the Iowa DOT (see Figure 52).

Figure 52. RFID-based wireless concrete monitoring system (WAKE, Inc.)

A significant advantage of the use of the proposed system for temperature monitoring of concrete is that the temperature data can be wirelessly transmitted directly to the construction staff and used to alert project staff to temperature-related events in the concrete, such as freezing or elevated curing temperatures. In addition, models to forecast the future strength of the concrete can be incorporated into the system, which is very helpful for future scheduling and decision-making.

Based on the continuous information available to monitor the maturity or strength of concrete in real time, decisions can be made more effectively for opening newly-constructed pavements, patches, or overlays much faster. This results in saving on construction time and reducing the traffic congestion due to lane closures.

The ASTM C 1074 (1998), *Standard Practice for Estimating Concrete Strength by the Maturity Method*, describes the procedure for estimating concrete strength using maturity concepts, based on the principle that concrete strength (and other properties) is directly related to both age and its temperature history. According to ASTM C 1074(1998), the maturity method is "…a technique for estimating concrete strength that is based on the assumption that samples of a given concrete mixture attain equal strengths if they attain equal values of maturity index."

ASTM C 1074 (1998) provides two types of maturity functions: (1) the Nurse-Saul function, which assumes that the rate of strength development is a linear function of temperature, and (2) the Arrhenius function, which assumes that the rate of strength development follows an exponential relationship with temperature.

The more commonly used Nurse-Saul equation is expressed as follows:

$$M = \sum_{0}^{t} \left(T - T_0\right) \Delta t \tag{1}$$

where:
M = maturity or Temperature-Time Factor (TTF) (usually in ^{o}C-hours or ^{o}C-days)
t = time interval being considered
Δt = time interval
T = average temperature of the PCC during the time interval (Δt) being considered
T_0 = datum temperature – the temperature below which PCC shows no strength gain with time (-10^{o}C is most commonly used)

The curves for maturity are built using test data from either compressive strength cylinders or flexural strength beams. In this research study, compressive strengths were determined in the lab by testing PCC cylinders at different ages. Figure 53 displays the maturity curve determined from wireless RFID temperature sensor data, as well as from other sensors, along with the laboratory-measured compressive strength data.

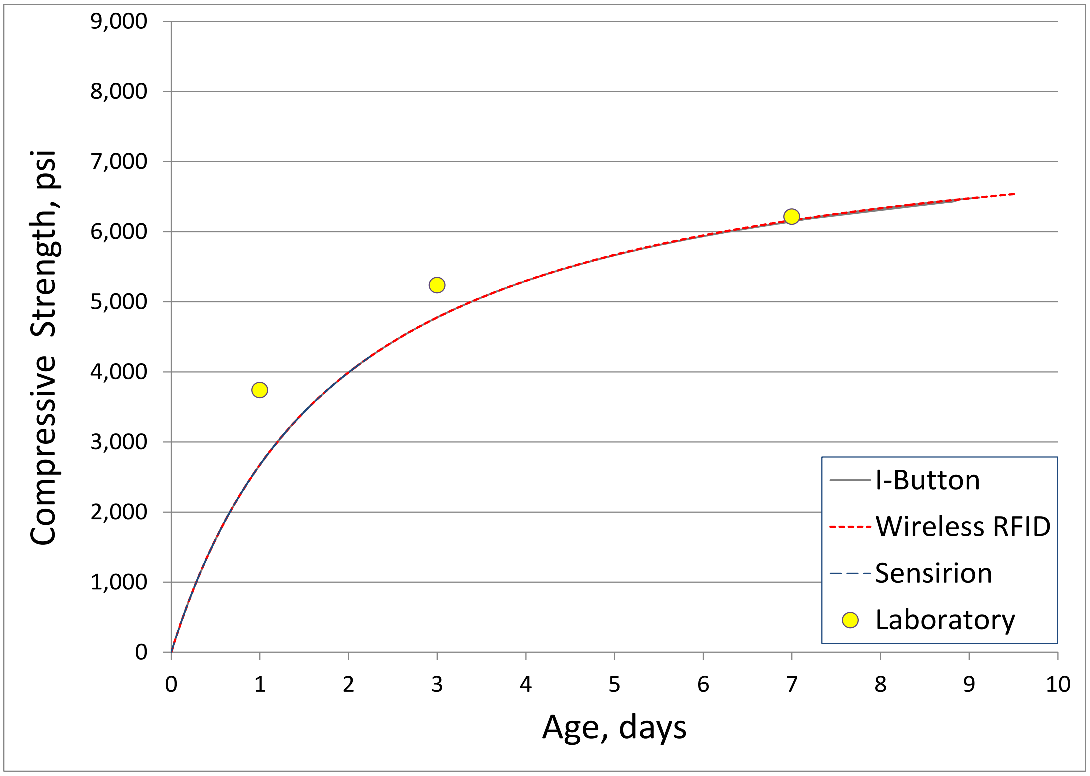


Figure 53. Concrete maturity curve

The RFID-based concrete monitoring system could also be used to monitor strength gain in concrete bridges, etc. In addition, questions like how many number of freeze-thaw cycles a concrete pavement section has undergone, was it frozen during its early strength gain, did the concrete get too hot, etc. could be answered, which is also useful in characterizing the early-age curling behavior of the PCC (DeFinis 2004).

Another major benefit is that the effects of cold or hot weather on mix designs containing certain materials could be studied using the RFID-based concrete monitoring system. For instance, by placing concrete containing fly ash/ground granulated blast furnace slag (GGBFS) (which slows down strength gain in cold weather) and monitoring the strength gain, a temperature-dependent specification (with the amount of fly ash/GGBFS) could be specified, rather than a date-dependent specification (DeFinis 2004).

Figure 54 shows the new i-Q350 series of wireless RFID tags by IDENTEC SOLUTIONS with the following enhanced capabilities:

- Equipped with Marker technology for selective locating of a transponder
- Communication range of up to 500 m
- Real-time data collection
- Advanced UHF RF technology
- Six-year battery lifetime
- Durable in demanding environments

Figure 54. Brand new i-Q350 series of RFID tags (IDENTEC SOLUTIONS)

It should be noted that the RFID tags equipped with temperature sensors by IDENTEC SOLUTIONS have been successfully utilized in a number of recent infrastructure applications. A recent study extrapolated that the cost-savings benefit (through reduced wait time) per pour would be approximately $2,000 if the RFID system were used in combination with one third of the test cylinders typically used in the project (O'Connor 2006).

The IDENTEC SOLUTIONS i-Q32 temperature-tracking RFID tags were also used in the construction of the Freedom Tower, on the former World Trade Center site, in New York to determine optimum concrete strength and document curing rates (IDENTEC SOLUTIONS 2008, Daly et al. 2010). IDENTEC SOLUTIONS is also currently in the process of developing RFID-based humidity tracking tags, which are expected to have great potential in concrete infrastructure monitoring.

RESEARCH RECOMMENDATIONS TO THE IOWA DOT (TASK 4)

The Iowa Highway Research Board (IHRB) solicits proposals for projects that are innovative or explore longer-range advances in aspects of highway transportation annually. These projects may be "high-risk, high-reward" in nature, or they may be basic research leading to new fundamental insights, which, in due course, will result in substantive advances in design, construction, maintenance, instrumentation and monitoring, modeling, or management of highway-related projects. This project was one such study for which "seed funding" was requested with the goal of producing results holding promise for further useful development.

In consultation with the project technical advisory committee (TAC), the most relevant MEMS-based transportation infrastructure research applications to explore in the future phases of this research are highlighted and summarized in this section.

It has been hypothesized that ultra-low-cost radio-frequency (RF) MEMS sensors could be placed in infrastructural elements and even inside concrete and asphalt in large quantities to form a local RF MEMS sensor network for monitoring highway infrastructure.

The potential applications of MEMS- and nanotechnology-based sensor networks for transportation infrastructure applications are summarized in Table 2,which highlights the latest information on the availability of the associated MEMS sensors/systems (Liu et al. 2007).

Table 2. Potential nanotechnology- and MEMS-based sensor or sensor networks for transportation applications

MEMS/Nano Sensors and Systems	Potential Application	Availability
RFID sensor	Inventory tracking/pavement temperature monitoring	**Commercial products available:** • Q350 series by Identic Solutions (wireless) • GT-301 by GENTAG, Inc (wireless) • RFID chips by RF SAW, Inc (wireless) • PaveTag RFID by Minds, Inc. (wireless) **Research prototypes may be available, but no commercial product:** • Experiment for evaluating RFID signal attenuation through asphalt (Schwartz 2007) - using RadarGolf Ball and Alien RFID tags (wireless) • Advanced Design Consulting (ADC)

<table>
<tr><th>MEMS/Nano Sensors and Systems</th><th>Potential Application</th><th>Availability</th></tr>
<tr><td>Temperature sensor</td><td>Temperature monitoring and concrete strength estimation using PCC maturity concept</td><td>Commercial products available:
• Q350 series by Identic Solutions (wireless)
• Embed Sensor by MicroStrain, Inc. (wireless)
• IntelliRock by Engius (wired)
• GT-301 by GENTAG, Inc. (wireless)
• Temperaure iButtons by Maxim (wired)
• Digital temperature sensor by Sensiron (wired)
Research prototypes may be available, but no commercial product:
• Early age concrete property monitoring (Saafi and Romine 2005)
• Monitoring pavement condition using “Smart Dust” (Pei et al. 2007)
• Advanced Design Consulting (ADC)</td></tr>
<tr><td>Moisture sensor</td><td>Moisture/Humidity monitoring</td><td>Commercial products available:
• Humidity iButtons by Maxim (wired)
• Digital humidity sensor by Sensirion (wired)
Research prototypes may be available, but no commercial product:
• Early age concrete property monitoring (Saafi and Romine 2005)
• Monitoring pavement condition using “Smart Dust” (Pei et al. 2007)
• Passive, wireless inductor-capacitor (LC) resonant circuit (Ong et al. 2008)
• Advanced Design Consulting (ADC)
• Identec Solutions</td></tr>
<tr><td>MEMS accelerometer</td><td>Bridge and highway safety monitoring</td><td>Commercial products available:
• Triple-axis accelerometer board by freescale (wireless)
• 3-Axis Magnetic Sensor by Honeywell (wireless)
Research prototypes may be available, but no commercial product:
• Stop sign monitoring sensor network (Liu et al. 2007)
• Characterization of rolling resistance of a truck wheel (Iaquinta 2008)
• Safe inter-vehicle distance network (Iaquinta 2008)</td></tr>
</table>

MEMS/Nano Sensors and Systems	Potential Application	Availability
Load/strain/stress sensor	Monitor load condition and/or measure strain and stress information of pavements and briges	**Commercial products available:** • Sensor networks by Crossbow Technology, Inc. (Wireless) • Sensor networks by Sensicast (Wireless) **Research prototypes may be available, but no commercial product:** • MEMS strain sensor (Obadat et al. 2003) • Early age concrete property monitoring (Saafi and Romine 2005) • Microwave Weigh-In-Motion (WIM) sensor (Liu et al. 2007) • Smart pavement monitoring system (Lajnef et al. 2011)
Chloride detection sensor	Monitor the intrusion of rust-inducing salt	**Research prototypes may be available, but no commercial product:** • Smart Pebbles (Watters 2003)
Corrosion/crack detection sensor	Monitor corrosion rate, conductivity , coating heal monitor (CHM), water corrosivity, or hidden crack	**Research prototypes may be available, but no commercial product:** • John Hopkins "Smart Aggregate" (Darrin et al. 2004) • Comparative Vacuum Monitoring (CVM) Device (Sandia National Labs 2007) • Cement CNT sensors (Saafi and Kaabi 2009)
MEMS ultrasonic device	Monitor conditions at critical locations in steel bridge girders or truss members	**Research prototypes may be available, but no commercial product:** • Carnegie Mellon MEMS ultrasonic device (Ozevin et al. 2006)
Roadside air quality monitoring system	Monitor road side air quality	**Research prototypes may be available, but no commercial product:** • Roadside air quality monitoring system using integrated SensorChip CO_2 sensor of photonics, Inc. (Iaquinta 2008)
Traffic flow and vehicle detection system	Traffic flow monitoring and identification under different vehicular loadings	**Commercial products available:** • Sensys Networks, Inc. (Sensys Networks, Inc. 2007) **Research prototypes may be available, but no commercial product:** • Self-sensing pavement with piezoresistive multi-wall carbon nanotubes (MWNTs) (Han et al. 2009)

Pavement Strain Monitoring System (Potential Research Project #1)

Objective

The objective of this proposed research is to develop a pavement strain monitoring system for measuring and mapping localized strains induced by all loading events at all locations within a pavement section using an optimal number of sensors deployed at determined node locations. Such a system could provide many benefits in the context of highway infrastructure management including detection of possible damage, monitoring mechanical load history, and predicting the fatigue life of the monitored pavements, especially in the context of the Mechanistic-Empirical Pavement Design Guide (MEPDG) pavement design and performance modeling and validation (Lajnef et al. 2011).

Background

Under the FHWA Contract DTFH61-08-00024, researchers at Michigan State University are developing construction material-sized autonomous self-powered usage (battery-less) sensors for deployment in pavement structures to monitor the statistics of localized strain for early damage detection and future condition evaluation in the context of pavement network management (Lajnef et al. 2011).

The long-term sensing system design is based on the integration of a piezoelectric transducer with an array of ultra-low-power floating-gate computational circuits (Huang et al. 2010, Lajnef et al. 2008). Pavement fatigue life can be predicted using the strain-history stored in a series of memory cells using Miner's rule used in the MEPDG.

Lajnef et al. (2011) tested the proposed the "smart pavement monitoring system" and the associated interpretation algorithms under realistic conditions with complicated strain profiles. The pavement structure was modeled as an idealized layered system and truck traffic (class 9, class 11, class 5, and class 16) distributions were generated and applied as input loading to the pavement structure. An example of generated longitudinal strain response for the class 9 trucks at the bottom of the viscoelastic HMA layer is shown in Figure 55.

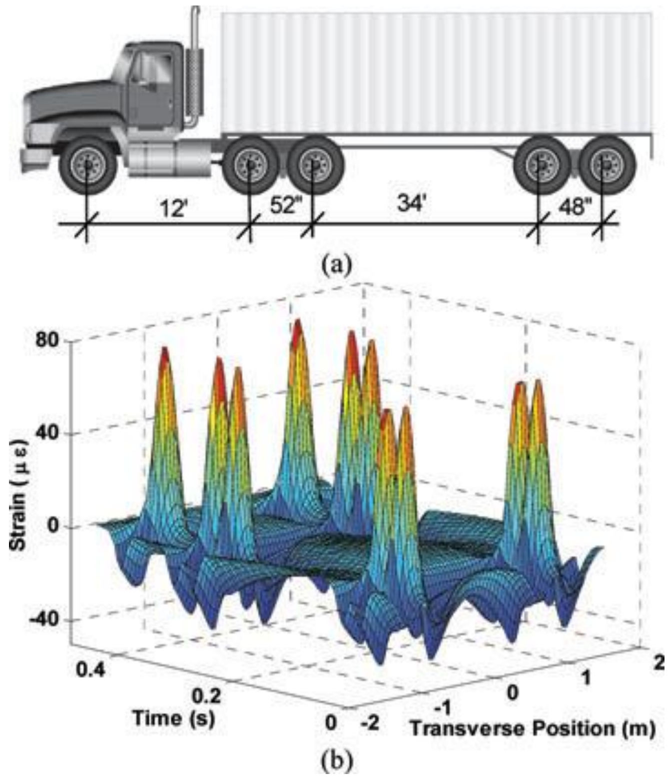


Figure 55. Example of generated longitudinal strain response for the class 9 trucks at the bottom of the HMA layer (Lajnef et al. 2011)

Overweight/Heavy Vehicle Pre-Alert and Detection System (Potential Research Project #2)

Objective

The objective of this proposed research is to develop an overweight/heavy vehicle pre-alert and detection system for traffic stream characterization and law (load limit) enforcement. The high-speed weigh-in-motion (WIM) technology enables weighing vehicles without interrupting the traffic flow and serves two very important functions: screen illegally overloaded trucks to prevent premature deterioration of highway infrastructure and collect data for planning and management purposes.

Background

WIM systems are generally categorized according to the application (weight enforcement, data collection, etc.), type of sensors used in the system (bending plate, load cell, piezoelectric, fiber optic, etc.), portability (permanent, portable, on-board, etc.), and traffic speed (high speed being more than 20 mph over and low speed being less than 20 mph over) (Liu et al. 2006). To overcome the limitations associated with bending plate, load cell, and piezoelectric sensors, Liu et al. (2006) developed a MEMS-type low-cost strip WIM sensor based on microwave cavity theory (see Figure 56).

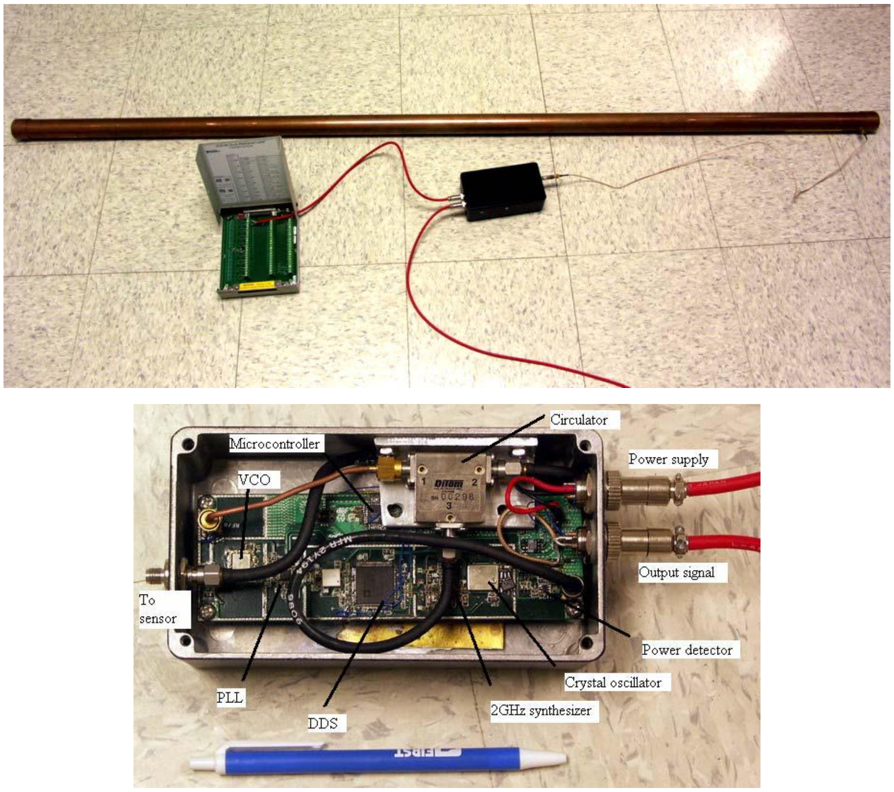


Figure 56. Microwave WIM sensor and its circuitry (Liu et al. 2006)

According to the researchers, it is easy to manufacture and install and the metal encasing is strong enough for the WIM application (without being broken in a tough environment). The sensor, encased in a cylindrical metal cavity, and its circuitry are shown in Figure 56.

Bajwa and Varaiya (2009) developed a low-cost WIM system using a MEMS accelerometer that estimates dynamic load of the moving truck based on transient vibrations of the pavement. The system was tested on a concrete pavement and was found to be immune to sound and other external noise on the road.

Furthermore, the data collected from the WIM sensors compared well with deflection data collected from a Falling Weight Deflectometer (FWD). Figure 57 shows the block diagram of the system.

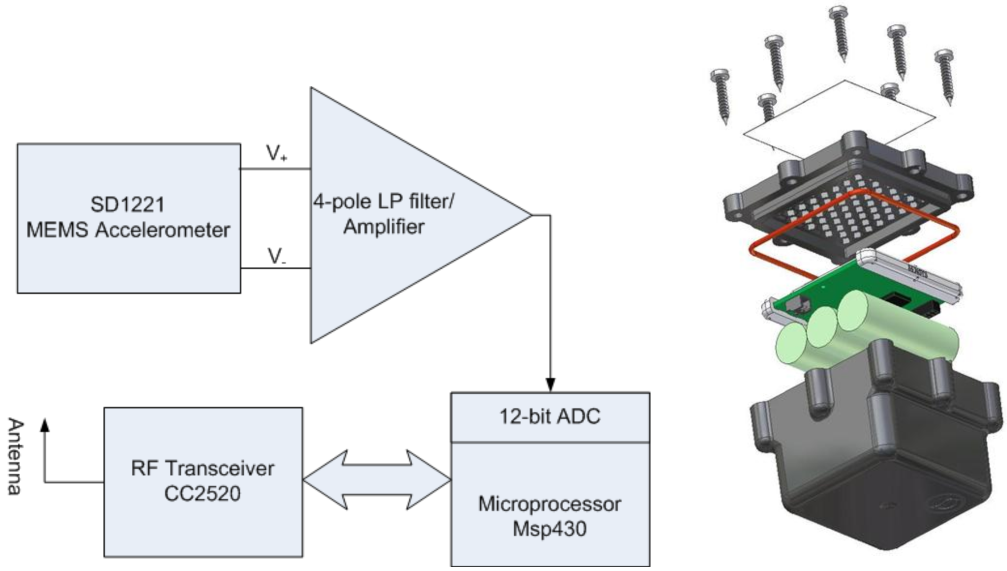


Figure 57. Block diagram of the WIM system which uses a MEMS accelerometer and the packaging of the sensors in a sealed case (Bajwa and Varaiya 2009)

According to the researchers, the same system has several potential applications, including axle counting, indirect measurement of pavement damage, replacement of FWD, structural monitoring, seismic monitoring, and airport runway monitoring (Bajwa and Varaiya 2009).

Critical Stop Sign Tracking/Monitoring System (Potential Research Project #3)

Objective

The objective of this proposed research is to develop a MEMS-based tracking/monitoring system that locates the whereabouts of critical warning/stop sign or other damage sustained by a warning sign and communicates that information back to a central location (like the DOT office). Such a system can be very beneficial in tracking missing stop signs or other important warning signs (such as those related to containment areas or hazardous materials) removed by either perpetrators or due to severe weather conditions (hurricanes, tornadoes, winter storms, etc.). Such real-time monitoring of road and warning signs can significantly contribute to the overall safety of transportation and other utilities and save money and maintenance time by eliminating the need for visual inspection (Liu et al. 2006).

Background

Liu et al. (2006) describe an overall demonstration system that uses MEMS magnetic compass and an accelerometer to detect the rotation of the stop sign and the static tilt of the stop sign, respectively. The data from both the magnetic compass and the accelerometer are acquired wirelessly using a radio system. Figure 58 shows the prototype demo system and the demo hardware under test.

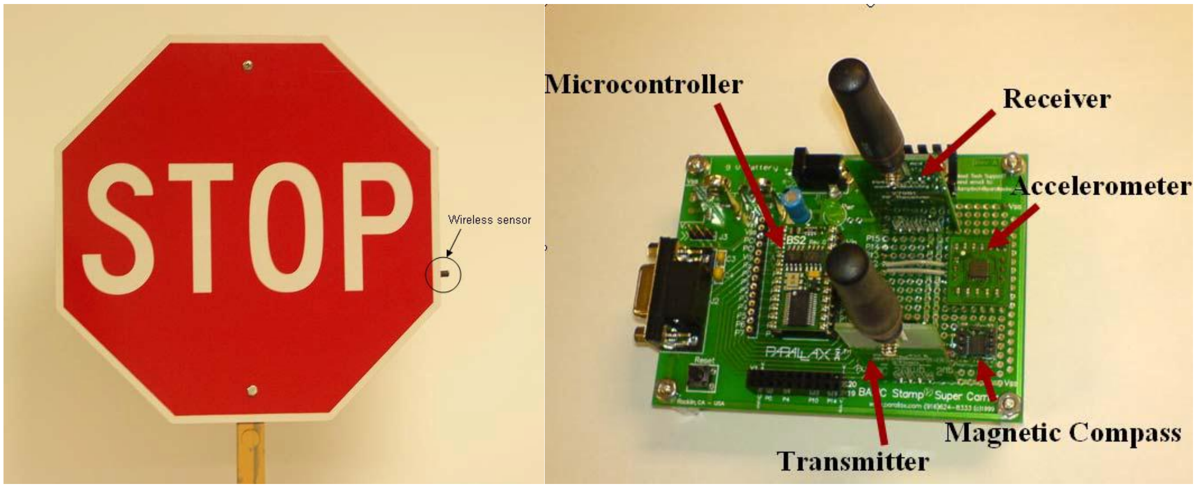


Figure 58. Prototype demo system for monitoring stop signs (Liu et al. 2006)

Traffic Flow Detection and Wrong-Way Vehicle Control and Warning System (Potential Research Project #4)

Objective

The objective of this proposed research is to develop a traffic flow detection system that would also serve as a wrong-way vehicle control and warning system.

Background

Sensys Networks, Inc. has developed a wireless vehicle detection system (VDS) that relies on a MEMS-based magneto-resistive sensor for vehicle detection (see Figure 59).

The traditionally-used inductive loop detectors to detect traffic are not only expensive to install, but require extensive lane closures, as well as significant saw-cutting of the roadway surface. In addition, the wiring, located either in underground conduits or in pull boxes, can fail and lead to data errors when subjected to severe environmental conditions (Sensys Networks, Inc. 2007).

It has been reported that this VDS can significantly lower the life-cycle costs associated with detecting traffic. A schematic of the Sensys wireless VDS is illustrated in Figure 59. The battery life of a wireless VDS sensor is reported to be 10 years.

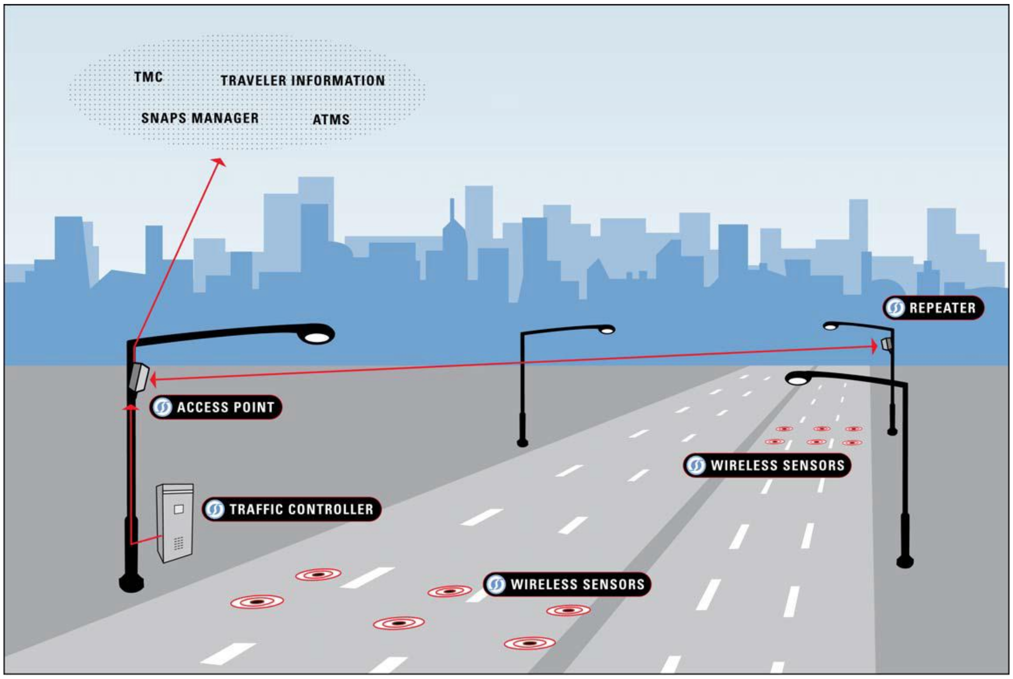


Figure 59. The Sensys wireless vehicle detection system (Sensys Networks, Inc. 2007)

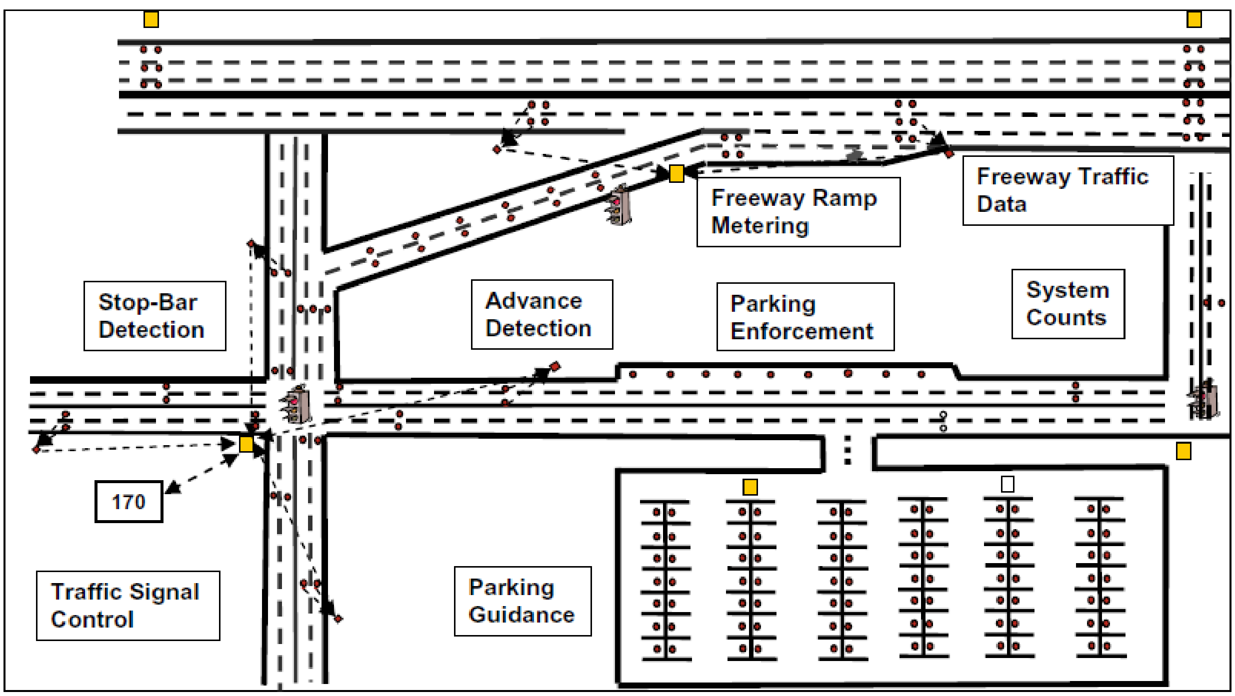
Figure 60 shows the steps in sensor installation, which involves boring a hole (4 in. diameter x 2.25 in. deep) at the desired sensing location, placing the sensor within the hole, so it's properly aligned with the direction of the traffic, and sealing the hole with fast-drying epoxy (Bajwa et al. 2011).

Figure 60. Wireless VDS sensor installation (Bajwa et al. 2011)

The performance and effectiveness of wireless MEMS-based VDS, as a potential replacement for inductive loop detectors, for the measurement of traffic parameters on freeways was evaluated by the California Center for Innovative Transportation (CCIT), with sponsorship from Caltrans. The wireless sensors were tested for timeliness of the detection system, completeness of records, reliability of the data (validity), and correctness of the data (accuracy). The overall conclusions of the study were highly positive, confirming the huge cost and time benefits that could be derived by installing the VDS in place of inductive loop detectors. It was estimated that the wireless VDS would costs $22,500 over a 15 year period as opposed to $49,500 for an inductive loop VDS and would require closure of 15 lane hours per station, as opposed to 56 lane hours with inductive loops (Margulici et al. 2006).

As with loop detectors, typical applications of wireless VDS include traffic monitoring, signal and ramp metering control, incident detection, travel time estimations, vehicle classification, and bottleneck analysis. In addition, the wireless VDS has a number of potential traffic applications (Margulici et al. 2006) as shown in Figure 61 (Haoui et al. 2008):

- Measure volume, speed, occupancy, presence, headway, gap, direction of travel, and vehicle length
- Support traffic monitoring stations on freeways and arterials
- Traffic signal control applications including stop bar and advance detection at intersections
- Ramp management at freeway entrances
- Replace existing failed loop detector stations
- Added flexibility in complicated configurations such as split roadways, flyovers, bridges, or when detection is required at long distances from the traffic signal controller
- Work zone management
- Traffic monitoring of secondary roadways



Small filled circles denote vehicle detection sensor node locations and small squares denote access points

Figure 61. Potential applications of wireless vehicle detection sensor network (Haoui et al. 2008)

Lan et al. (2011) have developed a novel vehicle detection and classification method by measuring and processing magnetic signals acquired from a single MEMS magnetic sensor. By exploiting the features of the magnetic signal, which is closely related to the characteristics of the vehicle, the approach proposed by Lan et al. (2011) can recognize the moving direction and the type of vehicle with a high recognition rate. The system's computational efficiency is further enhanced through the use of an improved one-against-all classification algorithm based on Support Vector Machines (SVMs). The overall structure of the vehicle detection system developed by Lan et al. (2011) is shown in Figure 62.

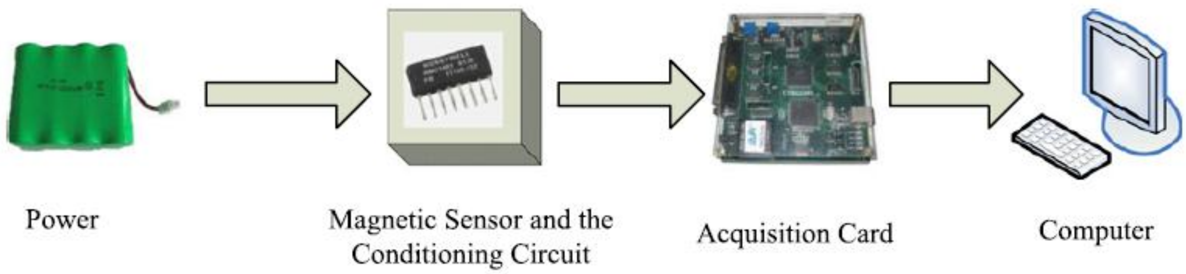


Figure 62. Overall structure of the MEMS-based vehicle detection system (Lan et al. 2011)

Black Ice Detection and Warning System (Potential Research Project #5)

Objective

The objective of this proposed research is to develop a road condition monitoring system for real-time detection of dangerous road conditions (particularly wet and icy).

Background

Pei et al. (2007, 2009) developed a "Smart Dust" wireless sensor network for monitoring pavement temperature and moisture presence to detect icy road condition. The system was developed based on off-the-shelf sensor network products from Crossbow and the TinyOS online forum.

An ice-detection algorithm, as shown in Figure 63, was developed and embedded into the sensors to categorize pavement surface conditions (dry, wet, frozen, and others) based on sensor measurements. Based on the proposed algorithm to detect icy road conditions, three types of sensors were selected for interfacing with the Mica 2 motes used in this study (see Figure 64). Mica 2 motes represent the third-generation mote module of the "Smart Dust" wireless network developed by Crossbow.

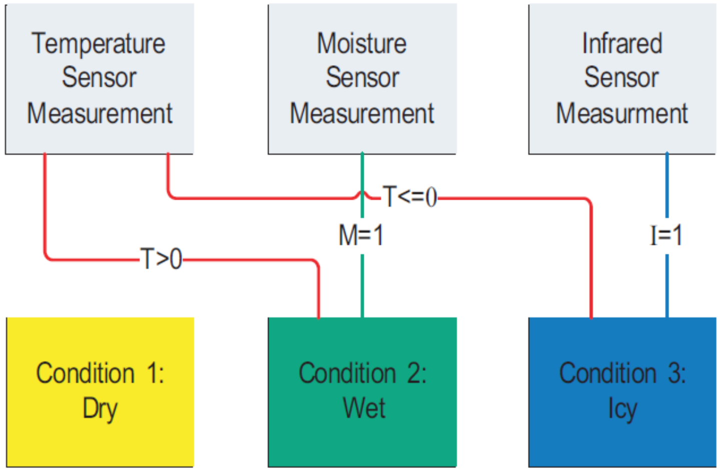


Figure 63. Ice detection algorithm (Pei et al. 2009)

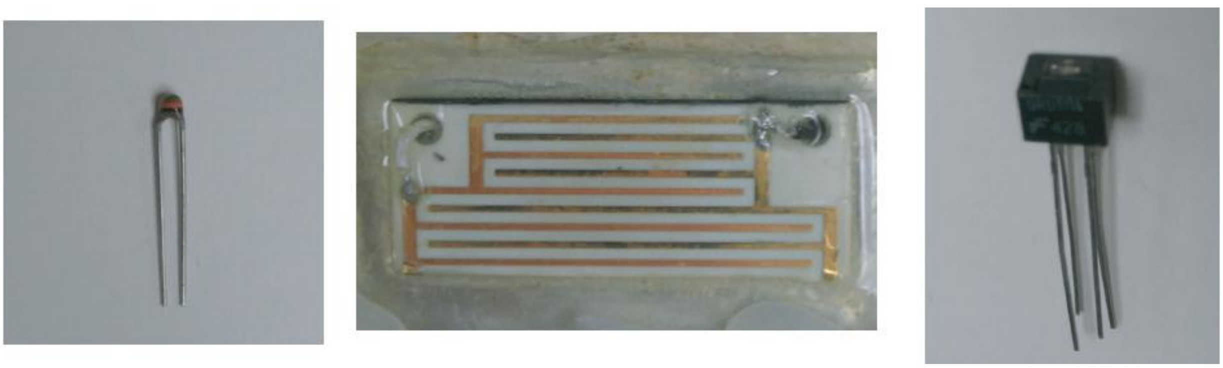


Figure 64. Sensors selected for interfacing with "Smart Dust" Mica 2 motes with thermistor (left), leaf sensor (center), and infrared sensor (right) (Pei et al. 2007)

Surge-time synchronization technology was used to enable the wireless sensor network to operate in a low-power consumption mode. A series of field tests conducted to test the survivability of fragile sensors in harsh roadway conditions led to the development of a Sensor-Road Button (SRB) (see Figure 65).

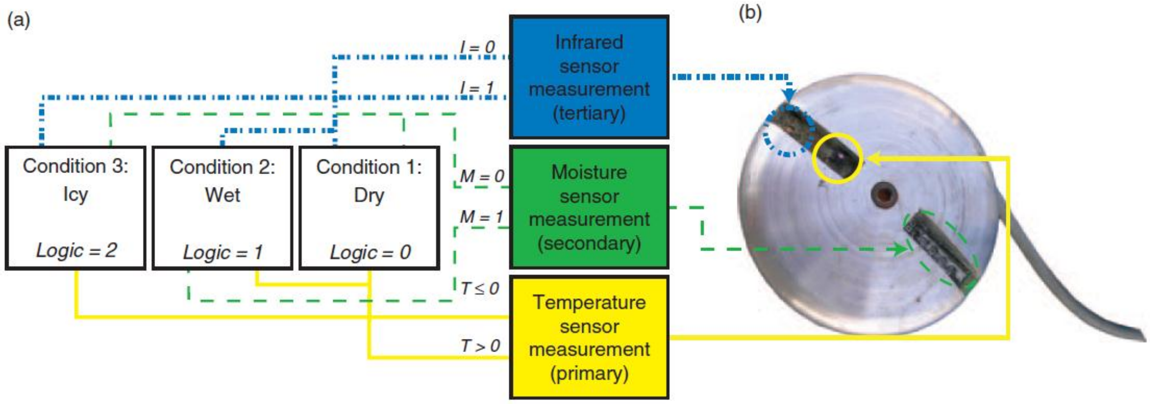


Figure 65. Sensor-Road Button (SRB) with location of three sensors (Pei et al. 2007)

Other Recommended Potential Research Projects

- Pavement Foundation (subbase/base/subgrade) Monitoring System
- Critical Infrastructure Condition Monitoring and Pre-Alert System
- Mass Concrete Monitoring System
- Bridge Deck Debonding Detection System
- Field Demonstration of Wireless RFID Concrete Monitoring System

SUMMARY AND CONCLUSIONS

Continuous monitoring and cost-effective assessment of infrastructure systems can help engineers to estimate risk at different stages and more efficiently plan maintenance and rehabilitation activities during the life-cycle of these structures. The development of novel "smart" structures by embedding sensing capabilities directly into the construction material during the manufacturing and deployment process has attracted significant attention in the context of autonomous SHM. Advancements in MEMS technology and wireless sensor networks provide opportunities for long-term, continuous, real-time SHM of pavements and bridges at low cost within the context of sustainable infrastructure systems.

The primary objective of this research was to investigate the feasibility of using MEMS in highway pavement infrastructure for SHM purposes. This feasibility study focused on investigating the use of MEMS and their potential applications in PCC through a comprehensive literature review, a vendor survey, and a laboratory study, as well as a small-scale field study.

This feasibility study explored the current state-of-the-art in MEMS for transportation infrastructure monitoring applications. Based on the comprehensive literature review, the latest information available on off-the-shelf MEMS devices, as well as research prototypes, for bridge, pavement, and traffic applications were synthesized.

The WAKE RFID wireless HardTrack Concrete Monitoring System, the Sensirion Digital Humidity Sensor, and the Maxim Thermochron iButtons were selected for the laboratory and field studies. A concrete slab form was fabricated to install the selected sensors. The mixed fresh concrete was carefully placed in the instrumented concrete form. The experimental test program consisted of four test phases (including a field test phase) based on different test conditions.

The test results validated the ability of the RFID wireless concrete monitoring system in accurately measuring the temperature both inside the laboratory and in the field under severe weather conditions.

Because the micro-sized MEMS devices are intended to be used in harsh environments, reliability is one of their most important properties. However, the reliability of MEMS products is still not well established given that their failure mechanisms are much more complex than those of simple ICs.

A number of factors, including but not limited to, whether or not they are embedded and how they are embedded into structures, the environment in which they operate, and the casing or packaging, will determine the reliability of these devices. The lack of adequate knowledge in this area is also contributed to by the hesitancy of MEMS manufacturing and packaging companies to share such valuable data. In general, MEMS devices that have been packaged in a way to safely protect them from the environment have been reported to be the most reliable (MEMX 2008).

In this research study, the wireless RFID sensors (the HardTrack Concrete Monitoring System) were the ones that survived the severe freeze-thaw conditions imposed during the field experiments. All of the wired sensors failed and the RFID tag with the antenna didn't function properly after a few freeze-thaw cycles in the field environment. This could also be partly attributed to the malfunctioning of the wired systems connecting to the data acquisition box.

The wireless concrete monitoring system appears promising due to a number of benefits, including wireless transmission of temperature data to construction staff directly to alert them of freezing or elevated curing temperatures; development of future concrete strength forecasting models; monitoring of cold or hot weather effects on mix designs using certain materials; strength gain in concrete bridges, etc.; and characterization of early-age PCC curling behavior, etc.

In consultation with the project TAC, the most relevant MEMS-based transportation infrastructure research applications to explore in the future phases of this research are highlighted and summarized. These include development of a pavement strain monitoring system, an overweight/heavy vehicle pre-alert and detection system, a critical stop sign tracking/monitoring system, a traffic flow detection and wrong-way vehicle control and warning system, and a black ice detection and warning system.

In today's societies, multiple, but individual, operational infrastructures, such as transportation and power grids, exist together and are connected via physical, cyber, and logical interdependencies to function as a tightly-coupled, socio-technical system of systems with complicated behavior. Continuous, reliable operation and resilience of such critical, interdependent infrastructures is crucial for maintaining homeland security, economic prosperity, and the quality of people's lives. In addition, there is a pressing need given social, economic, societal, and environmental considerations to optimize resources. In consideration of this emerging scenario, the research team's vision of "sustainable smart highways" is depicted in Figure 66.

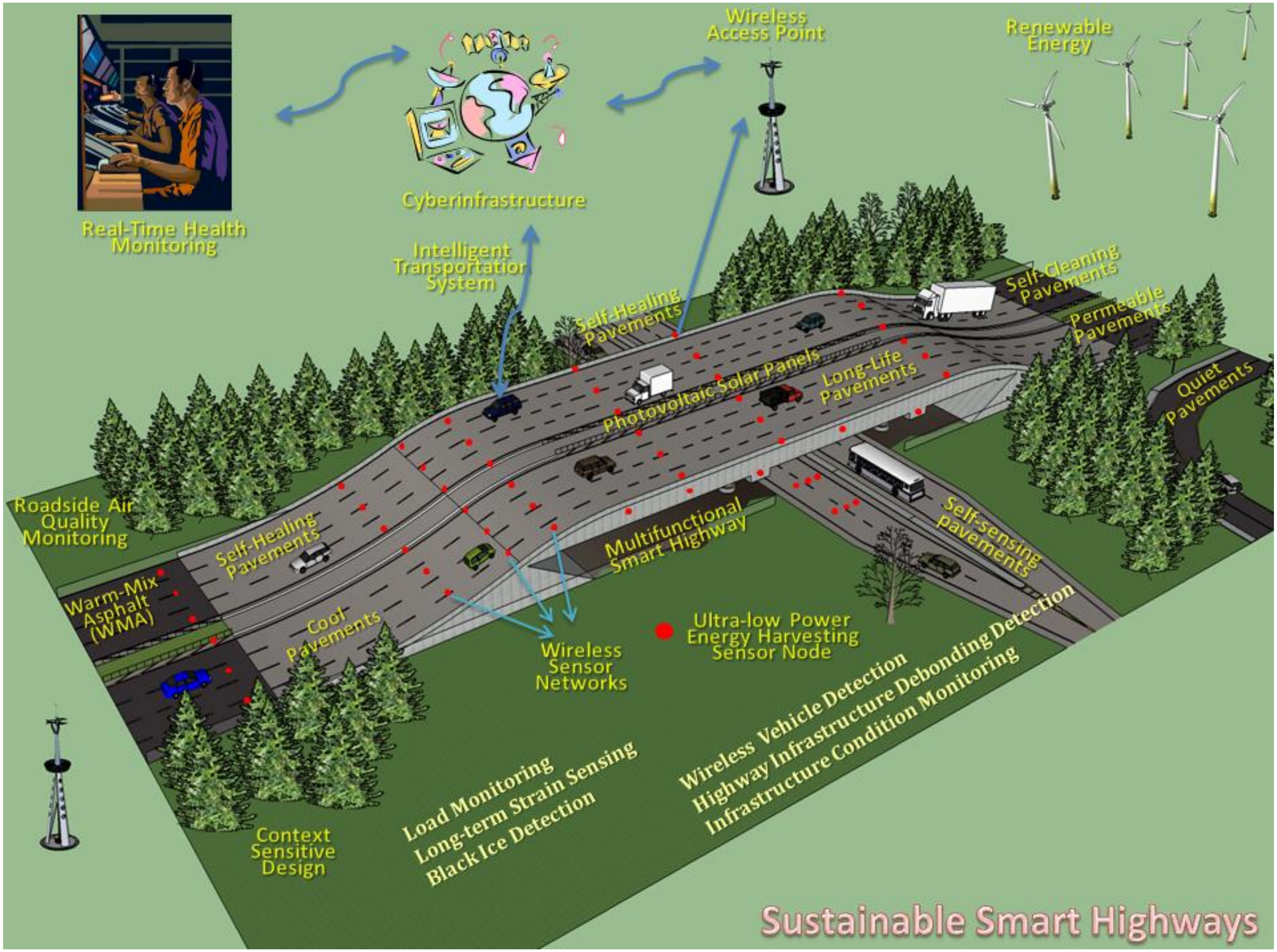


Figure 66. Research team's vision of sustainable smart highways for the future

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