Development of a Wireless MEMS Multifunction Sensor System and Field Demonstration of Embedded Sensors for Monitoring Concrete Pavements

tech transfer summary

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RESEARCH PROJECT TITLE
Development of a Wireless MEMS Multifunction Sensor System and Field Demonstration of Embedded Sensors for Monitoring Concrete Pavements

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The Program for Sustainable Pavement Engineering and Research (ProSPER) is part of the Institute for Transportation (InTrans) at Iowa State University. The overall goal of ProSPER is to advance research, education, and technology transfer in the area of sustainable highway and airport pavement infrastructure systems.

National Concrete Pavement Technology Center

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Problem Statement

Micro-electromechanical sensors and systems- (MEMS)-based and wireless-based smart-sensing technologies have, until now, rarely been used for monitoring pavement response in the field, and the requirements for using such smart sensing technologies have not yet been thoroughly researched or discussed.

Background

Pavement tends to deteriorate with time under repeated traffic and environmental loading. The structural health monitoring (SHM) concept can be applied as a systematic method for assessing the structural state of pavement infrastructure systems and documenting their conditions. SHM can be useful for civil infrastructure in saving both money and time by turning schedule-based maintenance into condition-based maintenance.

The development of novel “smart” structures achieved by embedding sensing capabilities directly into construction material during the manufacturing and deployment processes 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 structural health monitoring of pavements and bridges at low cost within the context of sustainable infrastructure systems. Thus, smart pavement SHM can be defined as long-term, continuous monitoring of sustainable pavement systems providing information about in situ pavement conditions to alleviate multiple safety concerns, including those related to pavement deterioration.

Traditional SHM approaches utilizing wired sensors have been used to track pavement response under environmental and traffic loads, including temperature, moisture, strain, stress, deflection, etc. However, over the past 20 years, fewer pavement instrumentation projects have been initiated, and nearly all have experienced negative issues such as high array density, wire damage, high installation costs and lengthy installation times, and the low survivability of wired sensors for long-term operation.

Recent achievements in MEMS technology make it possible to manufacture sensors using microfabrication techniques, and this kind of advanced/smart-sensing technology, including wireless sensors, shows vast potential for improving the traditional SHM approach.

Project Objectives

The primary objectives of this two-pronged research study were as follows:

- Deploy some of the promising commercial off-the-shelf (COTS) MEMS sensors developed for monitoring concrete pavement in a live field project
- Develop a wireless MEMS multifunction sensor (WMS) system capable of real-time, remote monitoring of strain, moisture content, and temperature in pavement concrete

Research Description

COTS MEMS sensors and wireless sensors were deployed in a newly constructed concrete highway pavement. During the monitoring period, the researchers obtained and analyzed temperature, moisture, and strain profiles for the pavement. The monitored data captured the effects of daily and seasonal weather changes on concrete pavement, particularly on early-age curling and warping behavior.

The sensors, however, presented issues for long-term operation, so, to improve performance, a ZigBee protocol–based wireless communication system was implemented for the MEMS sensors.

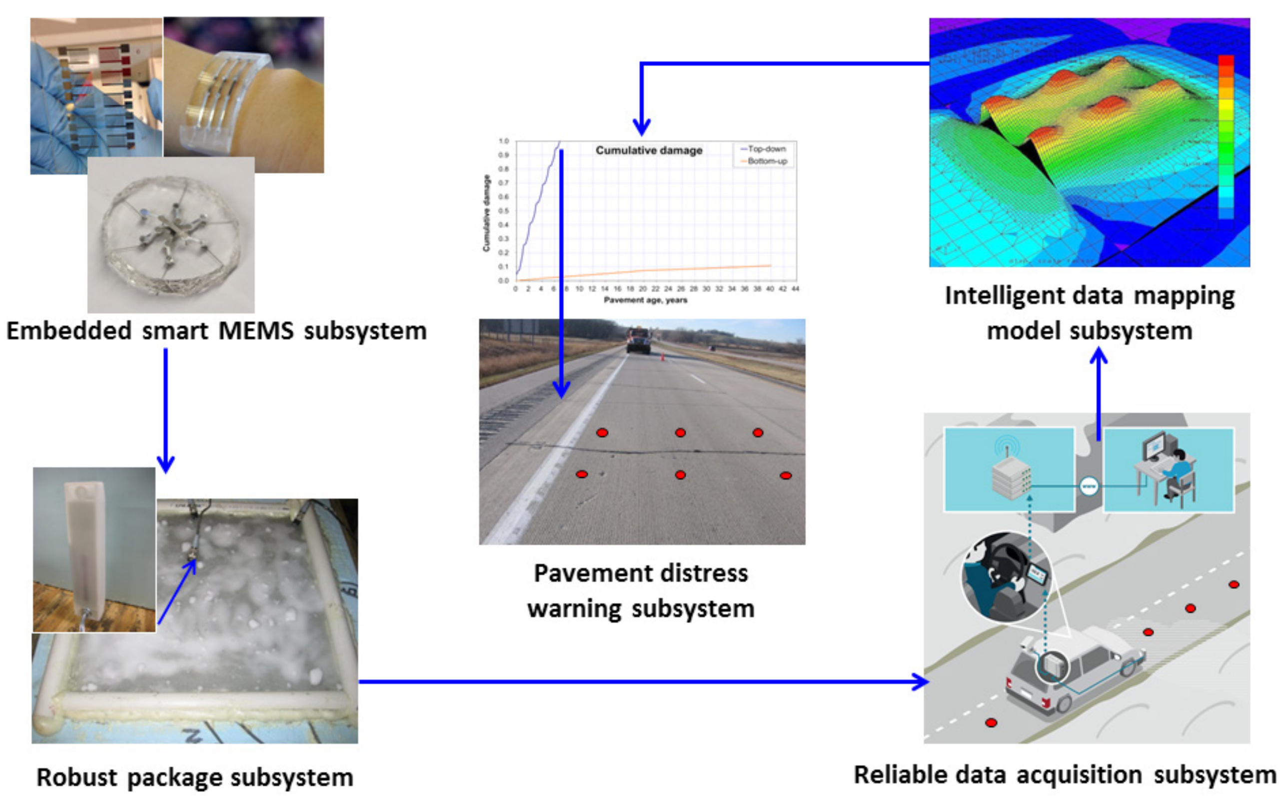
By synthesizing knowledge and experience gained from a literature review, field demonstrations, and implementation of wireless systems, issues associated with sensor selection, sensor installation, sensor packaging (to prevent damage from road construction), and SHM for concrete pavement were summarized. The requirements for achieving Smart Pavement SHM were then explored to develop a conceptual design for smart health monitoring of both highway and airport pavement systems for next-generation pavement SHM.

The following MEMS sensors were developed in-house through this research study:

- Nanofiber-based moisture sensors
- Graphene oxide–based moisture sensors
- Flexible graphene small-strain sensors with liquid metal
- Graphene medium-strain and pressure sensors on polyimide tapes
- Three-dimensional (3D) planar and helical-structured graphene large-strain sensors
- Temperature sensors
- Water content sensors

In addition, MEMS temperature and water content sensors were integrated into one sensing unit, constituting a multifunctional sensor. A wireless signal transmission system was built for MEMS sensor signal readings.

The sensors were characterized, and sensor responses were analyzed using different applications. The sensors developed were installed and tested within concrete to demonstrate their capabilities for detecting changes in corresponding physical signals at the installed locations.

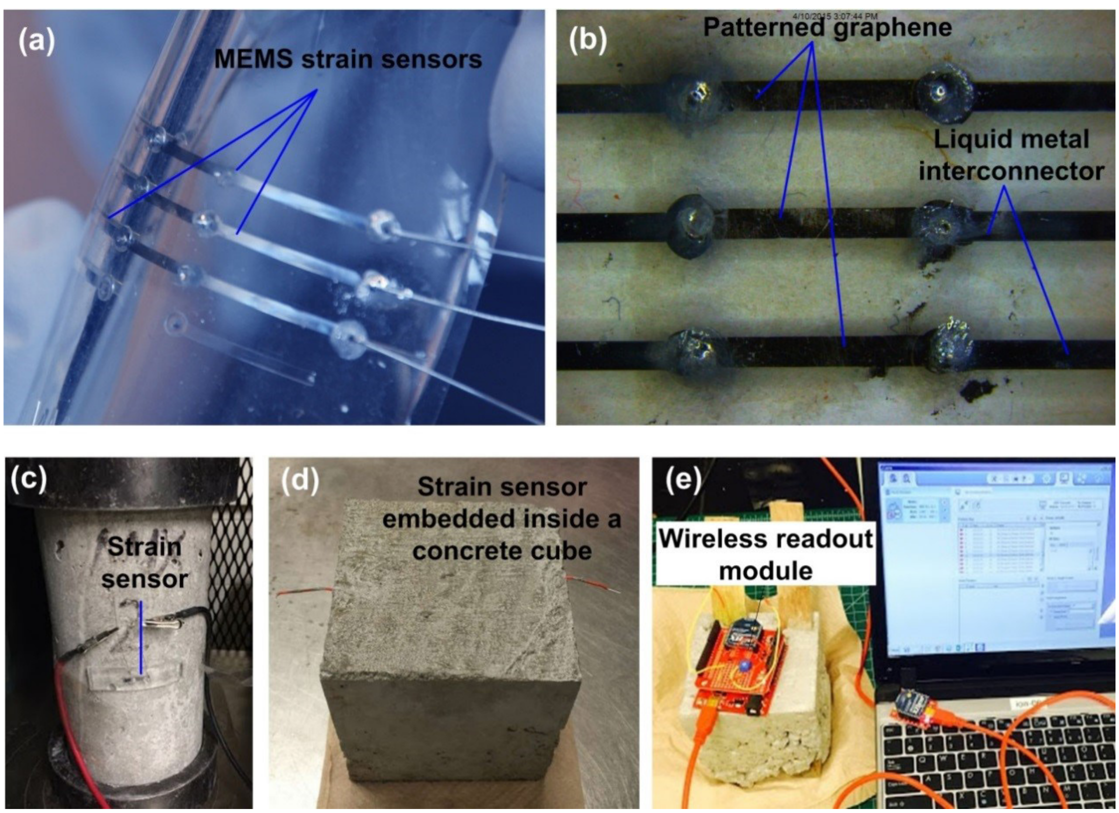


Architecture of smart pavement structural health monitoring (SHM) system

The architecture of the developed smart pavement SHM was comprised of five subsystems: an embedded smart MEMS sensor subsystem, a robust package subsystem, a reliable mobile data acquisition subsystem, an intelligent data mapping model subsystem, and a pavement distress warning system.

Key Findings

- A MEMS-based sensor system represents a type of promising smart-sensing technology that could be used to achieve a Smart Pavement SHM. Seven types of MEMS sensors developed in this research as single-sensing units can measure moisture, temperature, strain, and pressure.
- A nanofiber-based moisture sensor is a novel relative humidity/moisture sensor with a sensitivity about three times greater than that of conventional moisture sensors.
- A graphene oxide–based moisture sensor exhibits high sensitivity to humidity with a short transient response time and good repeatability. A cost-effective method for forming large-area graphene oxide film for sensing applications was developed.
- A flexible graphene small-strain sensor using liquid metal can measure either unidirectional or multidirectional strain changes in concrete. The wireless signal transmission system built for MEMS sensor signal readings demonstrated reliable communication at up to 160 ft.
- Graphene-based medium-strain and pressure sensors on polyimide adhesive tapes have the unique advantages of easy installation, structural flexibility, and simple cost-effective fabrication procedures.
- 3D planar and helical-structured graphene large-strain sensors have the capability to sense applied strain and pressure from all directions.
- Different sizes of the MEMS-based temperature sensors developed can be used either as single sensors or as part of a multifunctional sensor system.
- The multifunctional MEMS sensor system as developed can measure both temperature and water content inside concrete.
- The ZigBee protocol¬–based wireless network implemented to support the MEMS sensors demonstrated reliable communication and achieved a high success rate over a 150 ft span.
- The main reasons for cessation of COTS MEMS sensor functioning in the field included concrete paver operation, alkali-cement hydration reaction in concrete, corrosion of sensor wires, battery issues, harsh climate, and slab movement.



(a) Close-up of stretchable small-strain sensors developed in this study, (b) close-up of three small-strain sensors encased inside a hydrophobic elastomer, (c) strain testing on the surface of a concrete cylinder, (d) small-strain sensor embedded inside a concrete cube with two electric wires connected to the wireless transmitter and receiver outside the cube, and (e) demonstration of using the developed small-strain sensor for measurement of concrete strain

Future Research Recommendations

Based on the recommendations of the project technical advisory committee (TAC), future research directions related to MEMS-based transportation infrastructure research applications were identified and are summarized as follows:

- Development of chloride ion detection sensors for monitoring rust-inducing salts in concrete structures, detection of wrong-way of vehicle entry, overcoming challenges to pavement health monitoring using smart sensing technologies, and cost evaluation of a smart pavement health monitoring system
- Development of an array of flexible and even wearable strain sensors for monitoring 3D distribution of strains with a high spatiotemporal resolution
- Investigation of a more effective assembly method to allow the developed sensing elements to be integrated into a single package for convenient installation and data readout, which may require, to some extent, involvement of the semiconductor and MEMS packaging industries

Implementation Benefits and Readiness

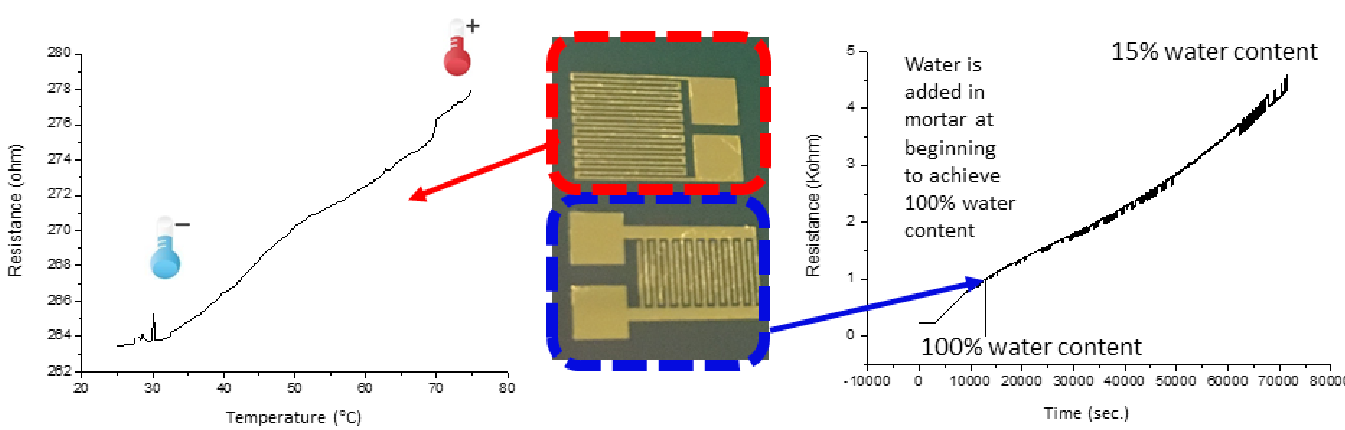
By detecting pavement distresses and damage early enough using smart sensing technologies, transportation agencies can develop more effective pavement maintenance, rehabilitation, and management programs and thereby achieve significant cost and time savings.

MEMS represent an innovative solution in infrastructure condition monitoring that can be used to wirelessly detect and monitor the initiation and growth of structural and material durability related damage in concrete structures. Wireless sensors can save both installation time and cost and do not present wire damage concerns.

A set of MEMS, along with the wireless signal transmission system developed in this research, can potentially aid transportation agencies in implementing reliable, real-time, and continuous health monitoring systems for transportation infrastructure systems to ensure that the systems perform their intended functions optimally during their service lives.

The research team has been tasked with expanding the findings and accomplishments for infrastructure health monitoring and management obtained during the Phase I and Phase II studies into other areas of transportation infrastructure systems, such as the following, in future research efforts:

- Flexible and composite pavement systems
- Geotechnical engineering and foundation systems
- Bridge structures and systems
- Mass concrete applications
- Construction quality control (QC) and quality assurance (QA)
- Construction management
- Critical infrastructure condition monitoring and pre-alert systems
- Monitoring of viaducts, drainage systems, and water channels
- Applications in unpaved and low-volume county and city roads (determination of freezing and thawing cycles and thawing periods using sensor systems, spring load restriction [SLR] guidance based on sensor data, and other applications)
- Overweight/heavy vehicle loading pre-alert and detection systems
- Detection of pavement reflection cracking using radio frequency identification (RFID)-based sensors
- Management of difficult-to-locate transportation assets using RFID-based sensors or similar methods
- Use of smart sensors and systems in vehicle-to-vehicle and vehicle-to-infrastructure control



A multifunctional MEMS sensor system (for temperature and moisture measurements) developed as part of this project