Applicability of Microelectronic and Mechanical Systems (MEMS) for Transportation Infrastructure Management

Final Report for Project MBTC-2056

Principal Investigator: Kelvin C.P. Wang

Graduate Research Assistant: Qiang Li

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Department of Civil Engineering
4190 Bell Engineering
University of Arkansas
Fayetteville, AR 72701
Email: kcw@uark.edu, Phone: 479-575-8425, Fax: 479-575-7168

ABSTRACT

It will be advantageous to have information on the state of health of infrastructure at all times in order to carry out effective on-demand maintenance. With the tremendous advancement in technology, it is possible to employ devices embedded in structural members for real-time monitoring of infrastructure health. Micro-electromechanical systems (MEMS) are miniature sensing or actuating devices which can interact with their environment to either obtain information or alter it. With remote query capability, it appears such devices can therefore be embedded in structures to monitor distresses such as cracking. Recently the potential for application of many of the developments in the nanotechnology field in the area of transportation engineering is growing. In this report a broad overview of the potential applications of various nanotechnology developments in civil and transportation engineering field is conducted. The focus is on the potential effects that the technology may have on aspects such as bridge, pavement, and traffic engineering. The most important challenges of the implementation of MEMS into transportation infrastructures are also addressed.

INTRODUCTION

Micro-electromechanical systems (MEMS) merge the functions of sensing and actuating with computation and communication to locally control physical parameter at the micro scale yet cause effects at much grander scales (Varadan etc, 2000). MEMS as devices have static or moveable components with some dimensions on the scale of a micrometer. MEMS devices can be classified under three broad categories: sensors, actuators and passive structures. Sensors are transducers that convert mechanical, thermal or other forms of energy into electrical energy; actuators do the exact opposite. Passive structures are devices in which no transducing occurs. A fourth classification, hybrid systems, is used for specialized applications. Micromachining and integrated circuit technologies are the foundation of sensors and actuators as well as of MEMS or microsystems. Figure 1 below is an illustration of the components of a microsystem.

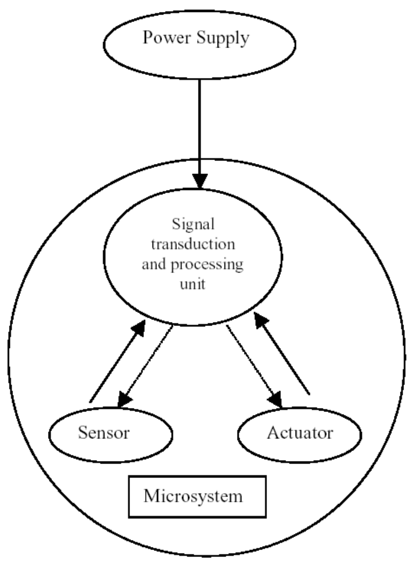


Figure 1 Components of microsystem (after Okine, 2003)

The actuation or sensing ability of MEMS depends on some intrinsic properties of the components such as piezoresistivity, piezoelectricity, or thermoelectricity. Piezoresistivity relies on the electrical resistance changing in response to mechanical stress. Piezoelectricity produces an electric field in response to strain and vice-versa. The objective of sensing is to transduce a specific physical parameter to the exclusion of other interfering parameters into electrical energy. An intermediate conversion step may be necessary, for instance, pressure or acceleration is converted into mechanical stress which is then converted to electricity. The choice of actuation depends on the nature of application, ease of integration with the fabrication process and economic justification.

Smart materials and structures technology is a new field of study that is finding its way into many applications in civil infrastructure systems. The applications include structural control, condition or health monitoring, damage assessment, structural repair, integrity assessment, and more recently in asset management, preservation and operation of civil infrastructure. The potential benefit here is improved system reliability, longevity, enhanced system performance, improved safety against natural hazards and vibrations, and a reduction in life cycle cost in operating and managing the infrastructure.

There is no doubt MEMS can lend itself to assist engineers in infrastructure management to have real time or quasi-real time information on the health of the infrastructure. Arrays of devices of the same or multiple types may be developed to meet various needs. A number of the same sensors can be used to improve reliability through redundancy and to improve stability through majority logic averaging to exclude the devices that are very different from the average, and then averaged again for the output. If arrays of units are distributed over the materials or structures, they may be used to obtain on-demand and programmable material properties and structural configuration.

The detailed description of nano and MEMS technology can be found in a large number of textbooks, proceedings and papers, which is beyond the coverage of this research. In this synthesis, a broad review of the potential applications of MEMS in civil and transportation engineering field is conducted.

MEMS IN TRANSPORTATION INFRASTRUCTURE

Nanotechnology and MEMS relate to fields of basic sciences, and engineering of electronics and mechanics, where phenomena on atomic, molecular, and millimeter levels are used to provide materials and structures that perform tasks that are not possible using traditional materials in their typical macroscopic form. Transportation engineering is concerned with the movement of people and goods over macro scale distances to ensure that the economy can function. A chasm exists between these two disciplines in terms of the operational scale (10^{-9} m to 10^{3} m). Therefore it is prudent to evaluate the potential effects of nanotechnology and MEMS developments on transportation engineering (Steyn, 2008).

New properties of MEMS products and smart materials have revealed wide applications for the development of new sensor systems and new smart construction materials for transportation engineering. These new materials will offer potential applications which will be beneficial for pavement engineering. Liu etc (2006) summarized the potential application of these innovative materials to pavement engineering as shown in Table 1.

The majority of the potential MEMS applications in transportation infrastructure condition monitoring will act as sensors. The advantage of these nano and MEMS sensors is their dimensions. With a scale of a micrometer, the sensors can be embedded into the structure during the construction process. These sensors can be used in monitoring temperature, measuring cracks, corrosion testing, monitoring ASR, and other related reactions in concrete, and for the reliability of welding units in structural steel (Liu etc, 2006). Since the MEMS sensors are fabricated with the microfabrication techniques commonly used in integrated circuit processing, they can be integrated with electronics to develop a high-performance system. Many applications in transportation condition monitoring are buried in a structure with no physical connection to the outside world. Therefore, they need to integrate the sensors and the communication system into one chip. This application is often made up of two parts: nano and MEMS sensors and communication system. Table 2 summarizes the MEMS sensors potential for transportation applications (Liu etc, 2006). These sensors can be categorized into three groups: nanosensor, microsensor, and bulky sensor. Nanosensor refers to a scale of from 10^{-9} m to 10^{-5} m; microsensor refers to a scale of 10^{-4} m to 10^{-2} m; sensors larger then 10^{-1} m are called bulky sensors.

Table 1 Potential Innovative Materials for Transportation Application (after Liu etc, 2006)

Innovative Material or Research on Chemical Kinetics	**Potential Application**	**Recommendations**
Self-healing polymers	Automatically heal cracks	Research is still under way
Nanostructure for building steel	Low carbon, high performance steel	This technology has never been applied before in transportation
Nanotube crack preventing material	Automatically heal structure cracks; increase structure strength	Research is still under way
Self-cleaning lotus leaf	Automatically clean pavement surface or traffic sign	Commercial product for transportation is not available
Superelasticity smart material	Self-rehabilitation concrete beams; blast protection of vehicular tunnels	Research is still under way
Shape memory alloy	Smart bridge	Successful application is transportation is available
Smart paints	Effective coating	Commercial product for transportation is in conceptual phase
Smart polymer coating	Radioactive contamination detection	Research is still under way
Steel and foam energy reduction barrier	Safer highway barrier	Successful product is available; cost and effectiveness needs more evaluation
Lead biosensor	Pavement lead contamination detection	Research is still under way
Smart fiber	Pavement environment monitoring	Commercial products are available
Helmholtz resonators	Noise-reduced pavement	Commercial products are available
Colloidal chemistry of ASR gels	Safer concrete	Research is still under way
Cement hydration kinetics	Safer concrete	Research is still under way
Fly ash reactivity characterization	Reduce fly ash	Research is still under way
Aggregate ASR potential tests	Safer concrete	Research is still under way
Delayed ettringite formation damage	Safer concrete	Research is still under way

Table 2 Potential Sensor Networks for Transportation Application (after Liu etc, 2006)

Innovative Material or Research on Chemical Kinetics	**Potential Application**	**Recommendations**
Nanosensor		
MEMS strain sensor	Measure strain information of pavement and asphalt	Commercial products are available and advanced research is under way
MEMS moisture sensor	Moisture monitoring	Commercial products are available
MEMS accelerometer	Bridge and highway safety monitoring	Successful commercial products are available
MEMS load monitoring sensor network	Monitoring load condition on bridge and highway	Successful applications are available
MEMS crack corrosion and crack testing and monitoring sensor	Crack and concrete corrosion testing and monitoring	Research is still under way
National Science Foundation sponsored research projects for MEMS sensors	Ultra-small sensor monitoring pavement temperature, moisture, pH and so on	Sensors are reported to be successful
Microsensor		
UH wireless moisture and temperature sensors	Monitor moisture and temperature information of pavement	Sensors are available at UH; cost and effectiveness are evaluated
RFID system	Inventory tracking/pavement monitoring	Low cost and effective sensors are available in market
Bulky sensor		
Low-cost microwave weigh-in-motion (WIM) sensor	Monitor highway load condition	Sensors are available at UH; cost and effectiveness are evaluated
Sensor networks with communication and control of smart materials and sensors	Communication between MEMS sensors and smart materials to better monitor and control pavement	Successful applications are available

MEMS in Bridge Structures

MEMS technologies are well suited to improve the performance, size, and cost of sensing systems. MEMS can be used in both monitoring and testing of transportation infrastructure systems. Several applications of MEMS in bridge engineering field are reported. In 1992, the FHWA began partnering with the American Iron and Steel Institute and the U.S. Navy to develop new, low-carbon, high-performance steel (HPS) for bridges. In 1996, the first of these steels was produced using a nanostructured material

(Kuennen, 2004). In low-carbon steel, copper nano particles form at the steel grain boundaries. The resulting microstructure changes make the HPS steel tougher, easier to weld, and more corrosion-resistant.

Differential settlement between bridges and pavements causes bumps or uneven joints at the bridge ends. When vehicles, especially heavy trucks, approach and leave bridges, the bumps cause large impact loads to the bridges and pavements. To automatically adjust forces among the bearings, Cai etc (2004) adopted a two-way memory effect of Shape Memory Alloy (SMA) material to make SMA actuators that can rise and fall to adjust their heights. SMA can also be used to manufacture smart strands. The applications of the smart bearings and smart strands can be used to develop a smart bridge as shown in Figure 2 (Liu etc, 2006). The smart bearings will adjust their heights through the shape memory effect of the SMA. This height adjustment will correct the unevenness problem as well as the internal forces induced from differential settlements, time- dependent deformations, and temperature changes. The prestress forces can also be adjusted to deal with cracking issues in both positive and negative moment zones. With the combined application of the smart bearings and smart strands, the bridge can adjust its internal force distribution and mobilize each element to adapt itself to different environmental loads.

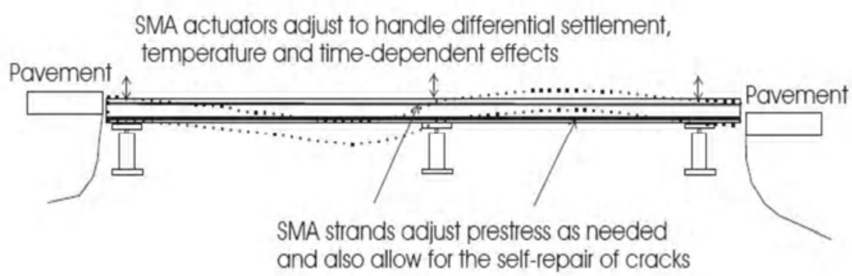


Figure 2 SMA smart material applied to bridge (after Cai etc 2004, Liu etc 2006)

The Ohio Department of Transportation and the Federal Highway Administration (FHWA) conducted a comprehensive market survey and laboratory evaluation to identify the most promising sensors and data-acquisition systems for infrastructure application, especially for highway bridge monitoring (Helmicki etc, 1995). This system was implemented on a typical steel-stringer bridge in Cincinnati for high-speed traffic and long-term environmental monitoring. The objective of this research was to provide an accurate measure of the state-of-health and alerts officials to bridge deterioration or failure. The system is shown in Figure 3. Furthermore, Iraqi etc (1999) added wireless ability to the above monitoring system.

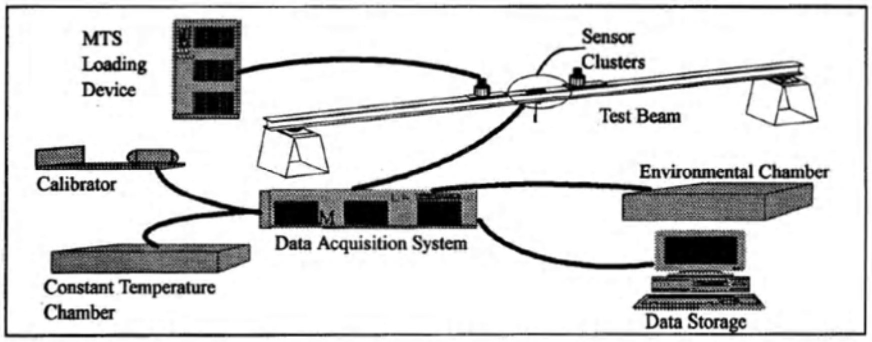


Figure 3 Bridge monitoring system Using MEMS Sensors (after Helmicki etc, 1995)

The MEMS accelerometers and pressure sensors can also be used to monitor the vibration and loads on bridges. The data obtained enable researchers to assess structural adequacy and conditions. Grosse etc (2004) developed a wireless MEMS sensor network using radio frequency transmission technique for large structural monitoring. The diagram is shown in Figure 4. It was reported that this wireless monitoring system with MEMS sensors could reduce installation and maintenance costs dramatically.

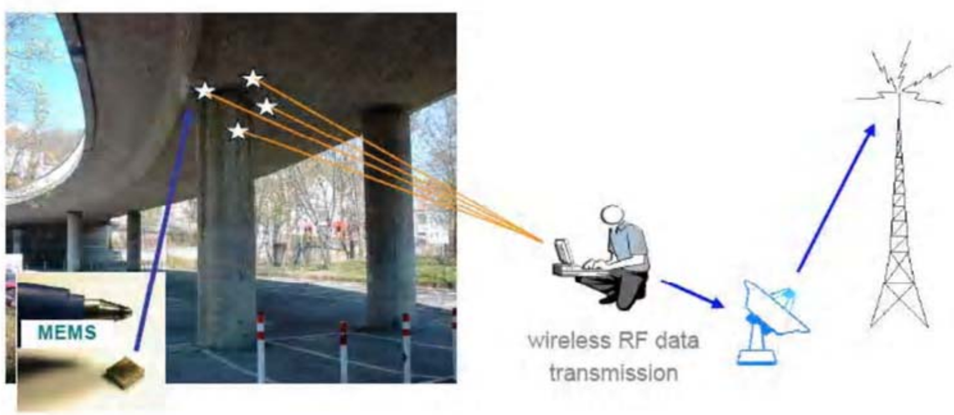
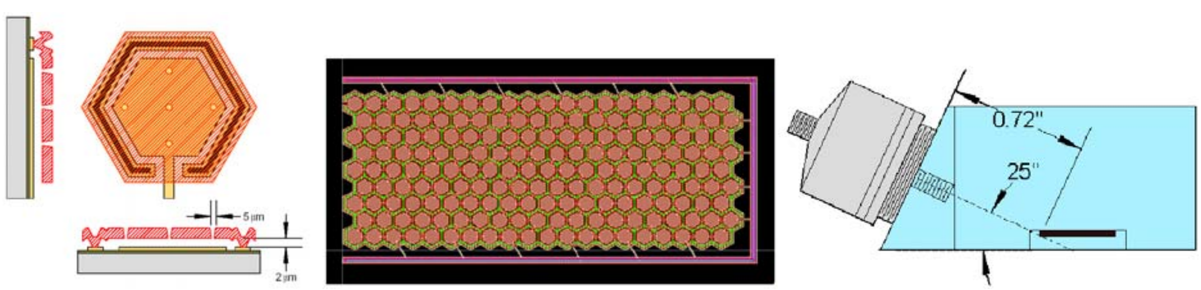


Figure 4 Diagram of wireless sensing of large structures using radio frequency transmission technique (after Grosse etc, 2004)

The University of Houston team (Liu etc, 2006) developed a remote bridge vibration monitoring sensor to measure highway bridge vibration. This system has a series of wireless accelerometers embedded into the pavement on the bridge. These low-cost accelerometers continuously measure the acceleration of the bridge in three axes and wirelessly send the data to a data collection center. The acceleration data are then analyzed to obtain bridge and load conditions.

To both improve technical performance and reduce cost of visual inspection for bridge girders, Oppenheim etc (2003) conducted a research for bridge inspection to study the use of MEMS ultrasonic devices to monitor conditions at critical locations in steel bridge girders or truss members. The devices would be affixed during erection and would function indefinitely without external power supplies or other connections. The devices would perform sensing and signal interpretation, and would report their findings remotely. The concept is to build an ultrasonic flaw detection system on a chip using a MEMS device as a receiver array with, a mm-scale piezoelectric element (part of the chip packaging) as the ultrasonic source. The system is intended to scavenge power from structural strains and to report results with fly-by polling using radio frequency communications. The concept requires the development of phased array signal processing, and/or signature analysis signal processing, to perform flaw detection (flaw imaging) from the fixed location of a resident transducer. The overall concept is a major innovation in instrumented flaw detection and monitoring, and is a paradigm shift when compared to non-instrumented methods such as visual inspection.



(a) (b) (c)

Figure 5 Ultrasonic MEMS Device Developed at Carnegie Mellon University (CMU)

(Oppenheim etc, 2003)

Figure 5 illustrates the design of the MEMS senor. A linear phased array using the MUMPs process is to make diaphragm type transducers with a natural frequency (in air) near 4 or 5 MHz (Figure 5 (a)). A capacitive-type MEMS device approaches the performance of PZT as an emitter only when operated at very small gaps, and therefore in the CMU design the phased array functions as the receiver while conventional PZT materials are used for the excitation. Figure 5 (b) shows a typical detector, approximately 0.9 mm x 2 mm, containing 180 diaphragm units shown Figure 5 (a).

Figure 5 (c) depicts the test specimen used to demonstrate phased array signal detection. The device was bonded to a plexiglass specimen using adhesive, and a commercial transducer with a nominal diameter was mounted to the specimen as the signal source. The baseline of nine detectors appears as the heavy line in Figure 5 (c), with a distance of 18 mm (0.72 in) between the signal source and the nearest detector. The purpose of the test was to obtain the distance from the transducer to the source, and the orientation angle, in the plane as pictured, using phased array signal processing. The test conducted by CMU researchers was successful.

MEMS in Pavement Engineering Field

Pavement condition monitoring and evaluation is important in many areas of pavement engineering, especially in pavement management. The in-service performance of the pavement depends on consistent, cost-effective and accurate monitoring of condition for properly scheduling of repair and maintenance. For the past decade, nondestructive evaluation (NDE) testing has played a major role in pavement condition monitoring, assessments and evaluation. However, several disadvantages limit the effectiveness of NDE. Recently, vigorous efforts have been devoted into developing sensing technologies and nano-technology in infrastructure condition monitoring.

For crack monitoring purposes, I. J. Oppenheim etc (2003) developed a MEMS transducer for an ultrasonic flaw detection system, which can be used to detect the initiation of a crack. A Krautkramer MSW-QC ultrasonic transducer was coupled to the plexiglass specimen and driven by a Krautkramer USPC-2100. Transducers with various resonant frequencies were used (1, 3.5, and 5 MHz). The transducer could be attached in different locations to provide for uniform illumination or off-axis incident illumination with various source distances and incidence angles. Further investigation on this MEMS sensor will result in an efficient pavement crack detector. It is found that carbon nanotubes with nano structures can be stiffer than steel, and can also be resistant to damage from physical forces. When construction material, like cement, is incorporated with a large quantity of strong, firm, rigid microparticle, it forms a new composite material with great strength, equivalent to rebar-frame reinforced concrete in microscale, a crack-free material. This material was reported in Plaisted's paper (2003). Nancy Sottos etc (Liu etc, 2006) developed a structural polymeric material with the ability to autonomically heal cracks, by incorporating a microencapsulated healing agent and a catalytic chemical trigger within an epoxy matrix.

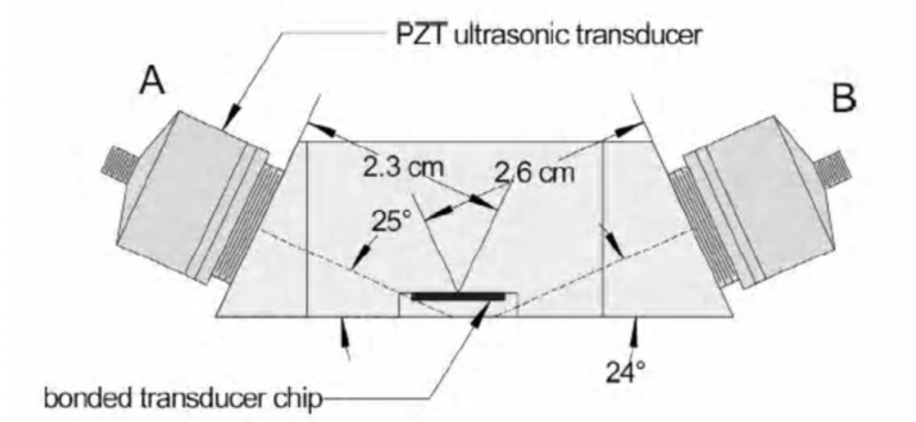


Figure 6 Drawing showing plexiglass test specimen with two off-axis locations for the emitting transducer (after Oppenheim etc, 2003)

The MEMS strain gauge can be used to optimize the use of accelerated load testing facilities and to be applied to monitoring systems of asphalt pavement and concrete pavement. Garg and Hayhoe (2000) at National Airport Pavement Test Facility (NAPTF) developed a mechanical strain gauge in order to sense the asphalt pavement status in the airport. The Asphalt Strain Gages (ASGs) are used at the NAPTF to measure asphalt concrete (AC) strains. The objective was to measure AC strains at low speeds and heavy wheel loads. A research program sponsored by Virginia Transportation Research Council was conducted at Virginia Polytechnic and State University to reinforce the functionality of the strain sensor by adding the wireless ability to system (Duke, 2002) . The wireless system is shown in Figure 7. Using such wireless technology, multiple measurement sites can report to one central processing location, avoiding the need to string wires access long distances, which might require considerable effort as well as traffic control. Timm and Priest (2004) at National Center for Asphalt Technology (NCAT) also developed a real-time data analysis system using strain gauges to model real time asphalt pavement status. Ozyildirim (2004) successfully applied strain gauges to the evaluation of continuously reinforced hydraulic cement concrete pavement in Virginia's Smart Road. Both the temperature and strain information are collected in this project to get a thorough monitoring of the crack status in the pavement.

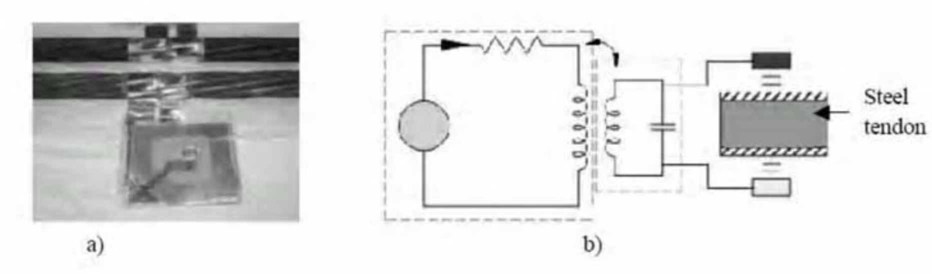


Figure 7 Wireless sensor system a) a wireless sensor for corrosion monitoring attached to a steel tendon; b) the schematic diagram (after Duke, 2002)

Networks of nanosensors embedded in roadways could provide real-time information to better manage congestion and incidents, or to detect and warn drivers about fast-changing environmental conditions, such as fog and ice. In recent years, more and more attention has been paid to MEMS-based moisture sensors. Harpster etc (2000, 2001, 2002) at the University of Michigan developed a MEMS-based passive moisture sensor systems. The MEMS passive wireless humidity monitoring system could record continuous remote monitoring of humidity changes inside miniature hermetic packages. It consists of a high-sensitivity capacitive humidity sensor that forms a LC tank circuit together with a hybrid coil wound around a ferrite substrate. The resonant frequency of the circuit changes when the humidity sensor capacitance changes in response to changes in humidity. Chia-Yen Lee and Gwo-Bin Lee (2003) developed the idea of MEMS moisture sensor. In this design, the movable electrode of a capacitance-type humidity sensor is made of microfabricated cantilevers coated with a material that absorbs water when exposed to humid conditions. The absorption of water molecules causes the upper layer of the cantilever to expand, and this induces a surface tensile stress. DeHennis and Najafi (2005) built a remote MEMS passive sensing system for relative humidity, temperature, and pressure. The working principle of the humidity (moisture) sensor in this system is based on the idea of the humidity-to-capacitance transducer, and it has a faster humidity response than the normal humidity sensor method. This high-speed capacitive humidity sensor integrated on a polysilicon heater. High speed is achieved using multiple polyimide columns having diameters of a few microns and allowing moisture to diffuse into them circumferentially. Yeo etc (2006) developed a fiber-optic based humidity sensor which can be used for the measurement of moisture absorption in concrete. The sensor was fabricated using a fiber bragg grating (FBG) coated with a moisture-sensitive polymer.

Radio Frequency Identification (RFID) transponders operating in the Ultra High Frequency (UHF) band, with the characteristics of longer reading distances, higher data rates, and smaller antenna sizes, can be used for pavement inventory tracking. The UHF RFID tags attached on a vehicle in TxDOT are adopted to collect the inventory information while running on the street as shown in Figure 8. The research team at the University of Houston (Liu etc, 2006) is currently working on a passive RF MEMS sensor network. The sensor will be activated by the RF signal from a reader. These passive RF MEMS sensors will collect the pavement information and send it to the reader.

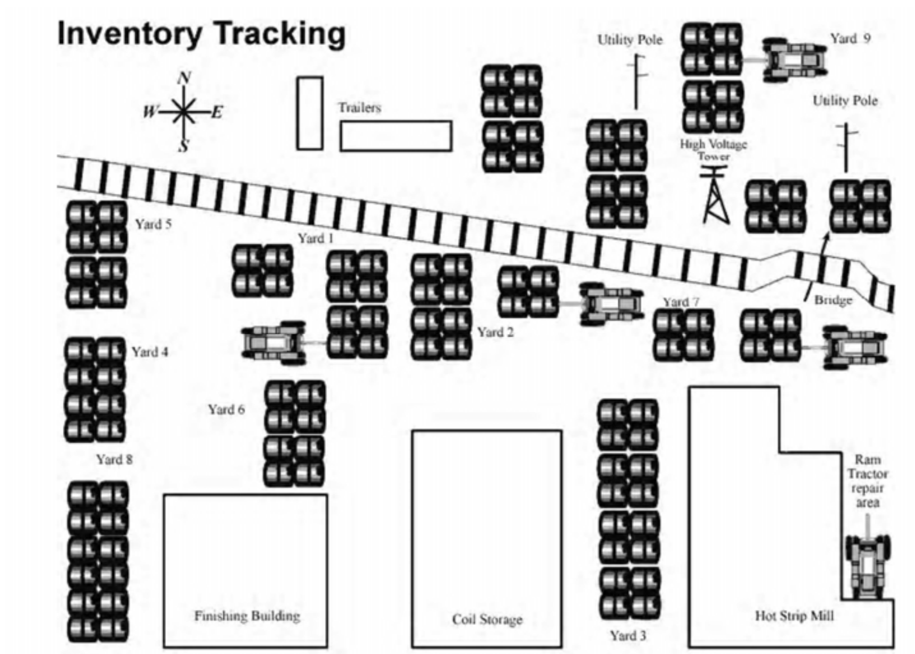


Figure 8 Demo of RFID inventory tracking (after Current Directions Inc., and Liu etc 2006)

Besides inventory tracking for TxDOT, RFID architecture can also be utilized as a highway or bridge monitoring system, as shown in Figure 9.

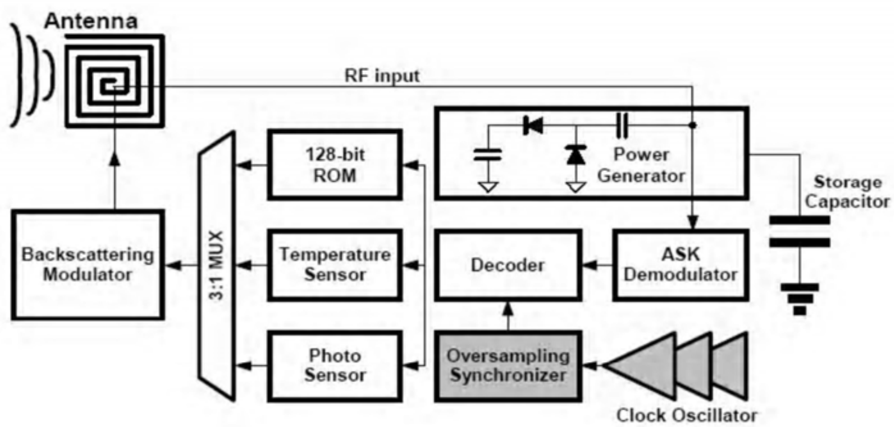


Figure 9 RFID sensor network (after Cho etc, 2005)

MEMS in Other Transportation Field

Barthlott and Neinhuis (1997) applied the lotus effect based self cleansing nano materials into traffic and work zone signage, and, in particular, traffic control devices, which require labor-intensive periodic washing to remove road grime and enhance visibility. On a hydrophobic easy clean surface, particles of dirt are just moved around by moving water, but on a lotus-effect surface, dirt and grime are collected by water drops and rinse off.

Brooks (2005) developed a technique utilizing the lotus effect at the Washington Department of Transportation (WSDOT). Their technology has the potential to solve even mundane problems like dirty signs. Coatings that mimic the properties of the lotus leaf, it may well lead to signs that shed dirt and never need washing.

An ideal safety barrier must be able to absorb or attenuate the very high energy resulting from vehicular impact, safely redirect the direction of an errant vehicle along the line of the barrier, and prevent crossover of the vehicle into the path of oncoming vehicles. Recently, new designs that use sandwich panels made with a facing material (such as aluminum, fiber-reinforced plastic, or wood) and a core made of either honeycombed materials (such as aluminum, Nomex, Aramid, etc.) or foam materials (such as polyurethane, polyvinylchloride, etc.) have been introduced in motor speedways, potentially in highways and bridge parapets (Sharp, 2004).

Smart fibers (Jsemmens, 2005) are regular fibers with a modified surface—some at only one end, and some at selected locations and intervals along each fiber – to change their light transmission or reflection properties in response to a change in their surroundings, such as the force to which they are subjected, moisture content, pH, etc. Therefore, each fiber is useful for monitoring changes in any one of these parameters (to which it is designed to respond) in the surrounding in which it is embedded, as long as the expected range of changes is within the dynamic range of the fiber's response.

In TxDOT Project 0-4509 (Liu etc, 2006), a low-cost Weigh-in-Motion (WIM) sensor using RF MEMS technology was developed. This WIM sensor can be made as short as a few millimeters or can be as long as a few meters. The cost of each sensor is less than $100, compared to a few thousand of dollars if conventional WIM sensors are used. This innovative WIM sensor is being developed and implemented in asphalt pavement for traffic load monitoring.

In FHWA/TX-07/0-5239-1 project (Liu etc, 2006), a fully functional smart stop sign was developed and tested. This smart stop sign is able to detect any malfunction including direction change, fall down, or tilt and report wirelessly to the TxDOT office using nanosensors and MEMS radio technology. A demo prototype system is shown in Figure 10. A stop sign with the smart tag are shown in Figure 11 and Figure 12.

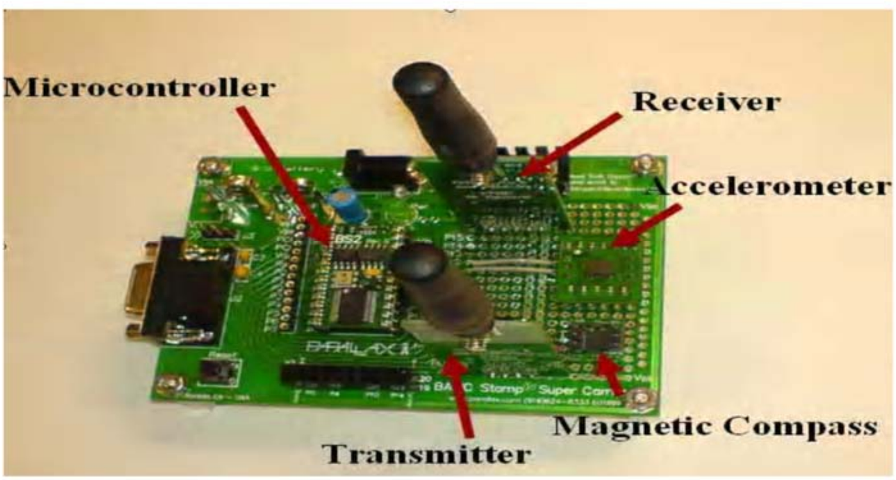


Figure 10 Prototype demo system (after Liu etc, 2006)

Figure 11 Demo hardware under test (after Liu etc, 2006)

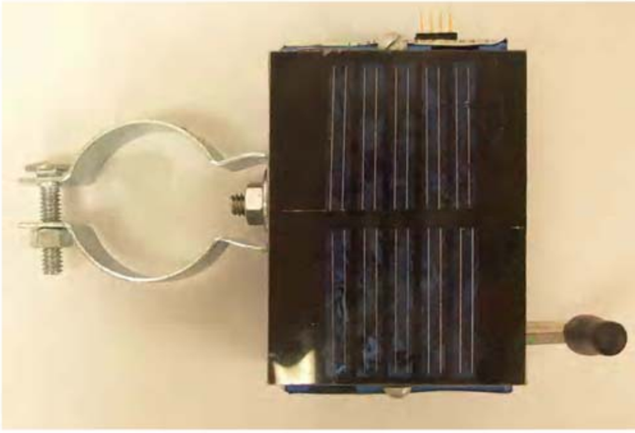


Figure 12 Top view of the demo MEMS sensor (after Liu etc, 2006)

Recently, using the Uni-Axial Strain Transducer (UAST), a micro-electro-mechanical system (MEMS) developed by Sarcos Research Co., a set of field strain data was collected under different passages of a train (Obadat etc, 2004). Data were also collected on the rail when no train was present in order to obtain the effect of noise on strain data. Using these data, the fatigue analysis software package called “SOMAT” was used to obtain a fatigue life. A three-dimensional finite element model was also developed for a particular railroad section, and a fatigue analysis carried out on the model using the computed strain history.

CHANLLENGES

As with most new technologies, a number of challenges exist during the initiation of applying the MEMS technology in the field. A short summary of selected challenges and limitations affecting the application are provided (Okine 2003, Steyn 2008).

●**Dimensional chasm**: The unique environment of the transportation engineer who works with large volumes of material should always be appreciated when evaluating potential applications of nanotechnology. The effects on manufacturing capacity and performance of the nanomaterials when combined with bulk aggregates and binders should be evaluated to ensure that the beneficial properties of the nanomaterials are still applicable and cost- and energy-efficient at these scales.

●**Upscaling of fabrication**: Current efforts in the field of nanotechnology are focused on the fabrication, characterization and use of these materials on a nanoscale (or at best on a micro scale). This leads to most of the development work focusing on very small quantities of material that is typically far removed from the type of quantities required for typical transportation infrastructure. One of the potential solutions to this is to focus on the nano materials to act as catalyser, thereby reducing the amount of nano material required substantially (Steyn 2008). Another viewpoint is that for many applications, the material does not necessarily have to be used on a nano scale to obtain a major improvement in benefits (Steyn 2008). This would be the case with reduction of the dimensions of cement, where a substantial improvement in strength can already be obtained through the large scale milling of the cement to a finer form than the traditional form. Although the cement may not be purely a nano material as yet (having at least one dimension of less than 100 nm), the benefits obtained would already be substantial (Garcia and Bernal, 2005).

●**Costs**: The costs of most nanotechnology materials and equipment are relatively high. This is due to the novelty of the technology and the complexity of the equipment used for preparation and characterization of the materials. However, costs have been shown to decrease over time (similar to developments with most novel technologies) and the expectations are that, as manufacturing technologies improve, these costs may further decrease. Whether the expected decreases will render the materials as run-of-the-mill transportation engineering materials will have to be seen, and depends largely on the benefits rendered through the application of these materials. Current opinion is that in special cases, the materials will enable unique solutions to complicated problems that cause them to be cost effective, which will lead to large-scale application of these specific technologies. In other cases the traditional methods for treating the problem may still remain the most cost effective. In addition, MEMS products are application specific rather than generic (Okine, 2003). The vast majority of applications require solutions that necessitate the funding and completion of an evaluation or development program.

- **Environmental and health issues**: As transport infrastructure are provided in the natural environment, all materials used in the construction and maintenance of these facilities need to be compatible to the natural environment and their effects on the natural environment should not be negative. Typical potential problems in this regard include leaching of materials into groundwater, release of materials into airways through the generation of dust and exposure to potentially harmful materials during construction and maintenance operations. One of the main reasons for using nanomaterials often specifically includes the different performance of the material on the nanoscale, and also the different effect that it has on the environment when used on the nanoscale. In cases such as improved methods for purification of water, the different effect on potentially deadly microbes in the water is specifically the reason why the nanomaterials are being used (Hassan, 2005; Savage and Diallo, 2005, Steyn, 2008). A clear distinction is thus required between controlled and sought-after effects on the environment and uncontrolled and unexpected effects on the environment.

- **Reliability and consistency**: the environment in which the MEMS devices has to operate and the possible effect of the environment on the performance of the MEMS device has to be assessed. Protection of the MEMS device against damage from installation or construction procedures as well as from contact with materials is paramount. Furthermore, the impact of the infrastructure system dynamics on the embedded device has to be evaluated and vice versa. It is obvious that the embedded devices will interfere with the strain field or act as "defects" within the material. An embedded MEMS device therefore may disturb the strain field. 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?" The effect of embedding a large number of MEMS devices in civil infrastructures cannot be ignored.

- **Acceptability and compatibility**: There is a need to evaluate the impacts of embedded devices on the whole construction process. This will influence to a large extent the acceptability of the product for monitoring of civil infrastructure systems. Another issue to be addressed is the compatibility method of installation with current construction methods. There is the need to evaluate the impacts of embedded devices on the entire construction process.

CONCLUSIONS

In this report, an attempt is made to provide a general overview of application of MEMS and nano technologies for civil engineering and transportation. The synthesis provides information on current and potential applications, especially in bridge, pavement, and traffic. Several case studies in the literatures demonstrate that MEMS technology has the potential to offer significant benefits to the civil engineering and transportation field. Finally the challenges in the application of MEMS technology into transportation infrastructure systems are summarized.

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