TRANSPORTATION RESEARCH

CIRCULAR

Number E-C056 October 2003

The Future of MEMS

Microelectromechanical Systems in Transportation Engineering

TRANSPORTATION RESEARCH BOARD
OF THE NATIONAL ACADEMIES

TRANSPORTATION RESEARCH
E-CIRCULAR

Number E-C056, October 2003
ISSN 0097-8515

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Microelectromechanical Systems in Transportation Engineering

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Foreword

This circular is intended to introduce microelectromechanical systems (MEMS) into transportation engineering by providing the reader with the general concept and the issues related to their development and thereby capturing the reader's imagination. MEMS are a relatively new innovation in the integrated circuit field. Although there are a few developed applications in the medical and the automotive industries, there are no fully developed applications in infrastructure construction and maintenance.

The application of MEMS is limited only by the imagination. Use of MEMS in quality control, quality assurance, controlling of heavy equipment, and condition monitoring for asset management are a few potential applications. The first step in development is to imagine a need and an application. The most obvious would be an application in which one would take a macro sensor or control system and miniaturize it. But one must also consider applications where no macro device has ever existed. Because of their size and low cost, MEMS could make measurement and control strategies that were not possible with macro or discrete devices now feasible. MEMS have the problem of a high initial development cost. But once developed, MEMS can be mass-produced for a relatively low per-unit cost: $5 to $50 each.

I encourage the reader to use this document to stimulate the imagination. Imagine applications and dream of how the development process would work for your imagined application. Don't let your dream pass: bring it to someone with some experience in MEMS for further evaluation and development.

Although this circular focuses on issues related to the design and development of MEMS, future circulars will cover actual applications of these systems to transportation infrastructure. This circular received a general review by members of the Applications of Emerging Technology Committee and detailed peer review by members knowledgeable in the emerging area of MEMS. The reviewers' recommendation was to publish the material with the hope that it could serve as an introduction of MEMS to the transportation community.

Richard G. Griffin, Jr., *Chair*
Committee on Applications of Emerging Technology

The Future of MEMS in Transportation Infrastructure Systems

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Based on results from other fields, microelectromechanical systems (MEMS) have the potential to be embedded in transportation infrastructure members for real-time monitoring of transportation infrastructure health. MEMS are miniature sensing or actuating devices that can interact with other environments (provided no adverse reaction occurs) to either obtain information or alter it. With remote query capability, it appears such devices can be embedded in transportation infrastructure as testing and monitoring tools. This circular presents a general overview of MEMS and its application to transportation infrastructure systems. Both technological and theoretical issues are discussed. Furthermore, current and potential applications of MEMS in transportation infrastructure systems are presented.

The term microelectromechanical systems (MEMS) refers to a collection of microsensors and actuators that sense their environment and have the ability to react to changes in that environment with the use of microcircuit control (Varadan and Varadan, 2000). Other names include microsystems technology (MST) and micromachines. MEMS merge the functions of sensing and actuating with computation and communication to locally control physical parameters at the micro scale. Numerous duplicate devices joined together can cause effects at much greater scales. Figure 1 shows the main components of MEMS. In addition to reducing size and mass, other advantages of MEMS-based systems include low cost through mass production. Because MEMS are produced with the same processes as semiconductors, large-scale systems integration is possible on a single silicon chip.

Nagel and Zhagloul (2001) describe MEMS as devices that have static or movable components with some dimensions on the micrometer scale. MEMS devices can be classified into three broad categories (Maluf, 2000): 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. The actuation or sensing ability of MEMS depends on some intrinsic properties of the component such as piezoresistivity, piezoelectricity, or thermoelectricity. For instance, capacitive sensing relies on external physical parameters changing either the spacing or the relative dielectric constant between the two plates of a capacitor. Piezoresistivity relies on changes in electrical resistance in response to mechanical strain. Piezoelectricity produces an electric field in response to stress and vice versa. Nagel and Zhagloul (2001) underscore the importance of piezoelectric materials for MEMS because of their electrical–mechanical reciprocity.

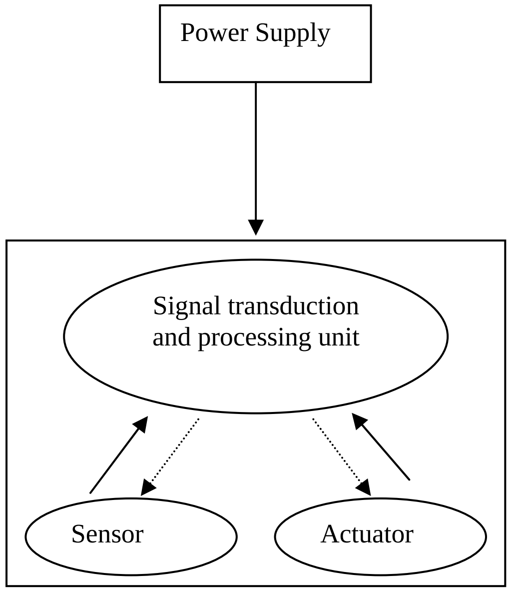

FIGURE 1 Components of a microsystem.

MEMS are not nanotechnology. While some MEMS devices have features that are measured in nanometers, MEMS and nanotechnology are fundamentally different. MEMS devices operate with dynamics that are determined by modeling matter as a continuum, while nanotechnology deals with matter's quantum mechanical behavior.

Distributed MEMS applications can be grouped into three classes (Berlin and Gabriel, 1997):

- Smart particles distributed in the environment, in which the location of the devices relative to one another varies over time;
- Active surfaces, in which the devices are permanently attached to a surface; and
- Smart structures, in which the MEMS element is fixed in place and interactions are coupled to one another through the dynamics of the material to which they are attached.

Smart materials and structures is a new field of study that is finding its way into many applications in transportation infrastructure systems, including structural control, condition or health monitoring, damage assessment, structural repair, and integrity assessment. The potential benefits here are improved system reliability, longevity and enhanced system performance, improved safety against natural hazards and vibrations, and a reduction in life cycle cost in operating and managing the infrastructure. The potential ability of MEMS to accelerate these benefits has been demonstrated in aerospace and automobile applications. There is no doubt that MEMS can lend itself to transportation infrastructure applications. However, there are some general drawbacks: there are no generic MEMS products—rather they are application specific—and the vast majority of applications require unique devices.

The purpose of this circular is to present both theoretical and technological challenges of MEMS application within the transportation infrastructure context. The circular further presents an overview of MEMS application in transportation infrastructure and speculates on some potential applications.

DESIGN

The sequential steps common to making most engineered components also apply to MEMS: design, fabrication, material selection, packaging, and testing. Tanner (2001) depicts the process flow sequence as shown in Figure 2. Early design consideration includes identification of the general sensing or actuation mechanisms based on the performance required. The design process is not exactly analytical science but rather involves developing engineering models for the purpose of obtaining basic physical insights. Modeling, simulation, and optimization of the MEMS before manufacture, though complex and time-consuming, are nonetheless cost-effective. Various computer-aided design (CAD) systems have been developed; these include MEMSCAD and IntelliCAD. Though this software can provide valuable insight and visualization of the device operation, its universal predictive utility is questionable (Maluf, 2000).

Romanowicz (1998) presents the following logical development flow of the modeling and simulation process:

1. Layout and design: Mask editors and design rule checkers;
2. Process simulation: Semiconducting process simulation and etch simulation;
3. Device simulation: Field solver implementing the finite element method (FEM), the boundary element method (BEM) equivalent circuits, and hardware description language;
4. System simulation: Equivalent circuits, hardware description languages, and analog and mixed module simulators;
5. Verification and measurement; and
6. Global simulation: Iterative execution of the above steps (optimization).

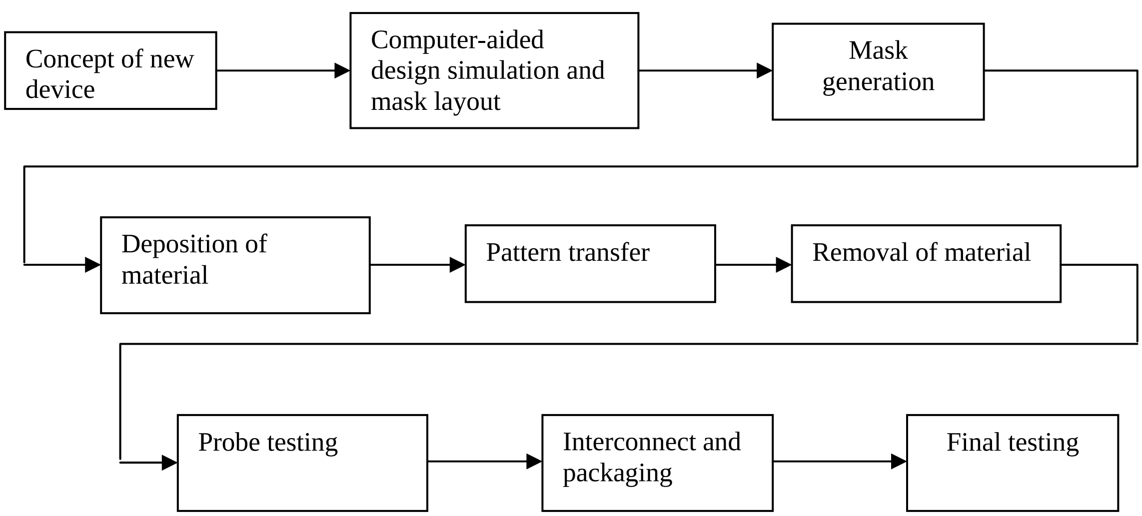

FIGURE 2 Process sequence for MEMS device fabrication [from Tanner (2001)].

Meshless techniques (Aluru, 1999; Ohns and Aluru, 2001) have been accepted as one of the most effective methods of CAD of MEMS structures. They are very attractive in MEMS applications because of the multiphysics and multiscale analysis, which are common requirements in MEMS simulation. Mesh generation for MEMS is very demanding. For example, an electromechanical system involving coupled elastic and electrostatic energy domains consists of a volume mesh for an electromechanical microdevice to perform finite element-based elastic analysis and the surface mesh of the same device to perform exterior electrostatic analysis based on the boundary element method (Aluru and White, 1997).

Liang et al. (2001) and Tay et al. (2001) developed a neural network-based method in the dynamic simulation of MEMS. The approach appears to be satisfactory in simulating the optimization of MEMS structures. Hubbard and Antonsson (1995) used cellular automata (CA) modeling as an etch simulator in the MEMS design process. The CA model is capable of simulating very complex geometries. Zhou et al. (2001) developed an evolutionary synthesis approach for MEMS design. The approach synthesizes functional MEMS devices by combining parameterized basic MEMS building components. These building components include beams, anchors, and electrostatic gaps.

SCALING

The scale effects have an influence on the design, fabrication, and performance of microdevices. The scaling effects of MEMS design and performance can be grouped into the following (Spearing, 2000):

- Quasi-fundamental,
- Mechanism dependent, and
- Extrinsic (or indirect).

Fundamental scaling factors can be derived purely by dimensional analysis— for example, the volume scales as the cube of length. Quasi-fundamental effects involve the assumption of slightly different models but still assume that physical constants or material properties remain independent of scale. Mechanism-dependent scaling extends the quasi-fundamental scale requirement when the scale of the microdevice controls the property of interest— for example, where crystal boundaries control strength and ductility at the macro scale, crystal boundaries would not be a factor at the micro scale. The extrinsic scales consider effects that cannot be attributed to a single physical factor— for example, because of fabrication limitations and the laws of physics, electrostatic fields become the force of choice at the micro level, while electromagnetic force is used at the macro level to convert electricity into motion.

The scaling properties of the microdevice can present a formidable barrier to both the economic feasibility and adequate performance of the device. One potential advantage of scaling of some MEMS devices to dimensions approaching the defect density of the material is that devices can be produced with a very low total count of defects, potentially yielding higher reliability of some MEMS devices than their macroscopic versions (Judy, 2001).

MATERIALS AND FABRICATION

Many MEMS devices and components can be made with the same set of materials and processes used for microelectronics. Design, fabrication, packaging, and testing are the process steps. According to Nagel and Zhagloul (2001), these steps determine both the performance and price of devices like integrated circuits and MEMS. Hence, they are considered a necessary critical issue for applying MEMS to civil infrastructure monitoring. Fabrication of MEMS devices can involve many steps. For example, in the application of MEMS to condition monitoring of axle bearings in railways, 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).

The principal materials include doped single crystal silicon wafers as the semiconductor substrate and deposited layers of polycrystalline silicon for resistive elements; aluminum (or copper or gold) as the principal conductor; and silicon oxide, silicon nitride, and titanium nitride for electrical isolation and protection. Recently new materials have been developed: the shape memory alloys that are used for actuators are one example. Piezolectric materials have become very useful in MEMS devices because of their electrical–mechanical reciprocity. Piezoelectric materials are capable of very high energy and power densities at micro scales. The high frequency of operation inherent in MEMS devices matches well with the relatively high-frequency capability of piezoelectric materials. The most commonly used piezo-materials in MEMS devices are lead zirconate titanate (PZT), zinc oxide (ZnO), and aluminum nitride (AlN). Recent advancements in environmental monitoring, especially in the area of chemical and biological sensors, have given rise to new materials applications in MEMS design.

Fabrication of MEMS falls into three categories:

- Surface micromachining,
- Bulk micromachining, and
- Molding process (collection of numerous and varied techniques).

Surface micromachining involves the buildup of micromechanical structures on the surface of a substrate by deposition, patterning, and etching processes. One of the processing steps involves the selective removal of an underlying film referred to as a sacrificial layer, without attacking the overlying film, referred to as the structural layer. Figure 3 illustrates the typical surface micromachining process (Madou, 1997). An example of the surface micromachining fabrication process is the micro accelerometers used in air bag applications.

Bulk micromachining involves etching into the substrate to produce the structure of interest. It can be done with either a wet or a dry plasma process, either of which can attach the substrate in any direction (isotropically) or in a preferred direction (anisotropically). The anisotropic process is called orientation-dependent etching (ODE). By exploiting the predictable anisotropic etching characteristics of single-crystal silicon, many high-precision complex three-dimensional shapes, such as V-grooves, channels, and nozzles can be formed. Figure 4 is an example of bulk micromachining along crystallographic planes. Deep reactive ion etching is a plasma process that is used increasingly to make MEMS, with structures that are over ten times as deep as they are wide. This is an important consideration in MEMS, where higher mechanical power of force levels is desired or in applications involving fluids such as nozzles (Spearing, 2000).

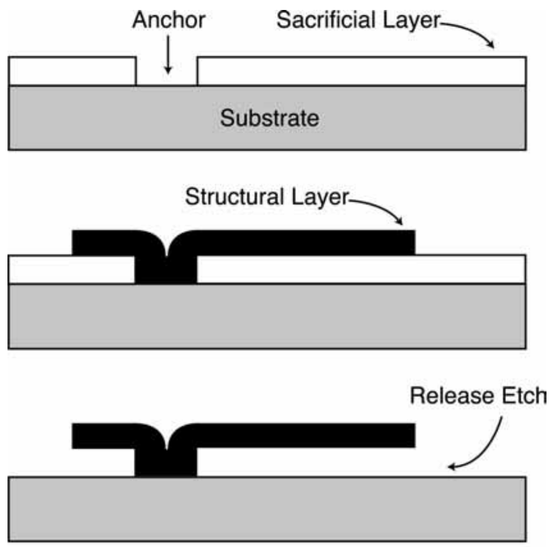

FIGURE 3 Surface micromachining

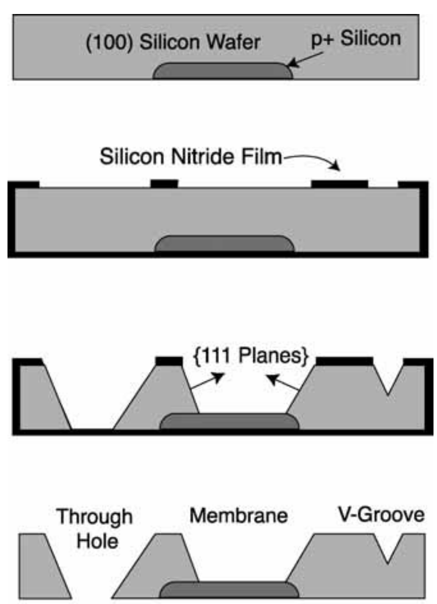

FIGURE 4 Bulk micromachining

The third fabrication process used in the creation of the mechanical elements of the device is the deposition of material into microfabricated molds. The most widespread use of this process is the LIGA (German acronym — lithography, galvanoforming, molding). It uses x-ray lithography for mask exposure; galvanoforming to form metallic parts; and molding to produce microparts with plastic, metal, ceramics, and their combination (Varadan and Varadan, 2000). Other methods include laser-induced etching and deposition of materials as well as ultrasonic and electron discharge milling.

The integration of circuits into MEMS devices can be achieved in the following ways (Judy, 2001):

- Fabrication separately and then assembly,
- Monolithic integration of integrated circuits (ICs) first,
- Monolithic integration of MEMS first, and
- Monolithic integration of both MEMS and ICs in a mixed process.

The use of any of the preceding methods depends on the material properties of the MEMS and economics. Finally, the most difficult step is the packaging of MEMS.

The packaging converts a MEMS structure into a useful assembly that can safely and reliably interact with its surrounding. In MEMS, packaging must first protect micromachined parts in broad-ranging environments. It must also provide an interconnect to electric signals and in some cases access to and interaction with the external environment (Maluf, 2000). Ko (1996) has proposed the use of a multilevel thin-film hermetic package. Each film layer performs one function of packaging, and adding different layers together enables the overall functions of the package to be achieved. In this case, thin film materials with good adhesion to each other and with controllable air or liquid permeability are needed. Packaging is very expensive and tends to offset the whole idea of miniaturization, since its relatively large dimensions tend to counteract the small size advantage of MEMS. Costs can run from 75% to 95% of the overall cost, because packaging is application specific, and no standards are in place.

COMMUNICATION AND POWER

The need to provide energy to effect sensing and actuation calls for the integrated power supply into the MEMS device. Application of embedded microsensors entails burying them in the structures with no physical connection to the outside world. Development of MEMS, therefore, requires the integration of the microsensor and actuator systems with micro power supplies. The conventional solution according to Williams and Yates (1996) is to use batteries, which have serious drawbacks: they tend to be quite bulky, contain a finite amount of energy, have a limited shelf-life, and contain chemicals that could create a hazard. A promising alternative to batteries is a miniature self-contained renewable supply. Two approaches have been proposed by Koeneman et al. (1997) . These are the use of a conventional macroscopic power supply external to the system or a power supply at the same scale as the microsensors, microactuators, and electronics. Either approach has advantages and disadvantages. In the case of the conventional external power supply, it is anticipated that the major problem will be interconnection of the circuitry to the microsensor and microactuators. Interconnection will raise a number of issues including layout efficiency on the silicon wafer, noise problems due to stray power connections, and cross talk between power lines and signal lines. A power supply at the same scale as the MEMS device will permit a truly integrated system that communicates with the environment through information exchange only rather than through exchange of both power and information. Sakikabara et al. (2002) discussed a micro-energy conversion device that can simultaneously convert light and microwaves to electric energy. The device consists of micro photovoltaic devices combined with a microwave antenna. The device is capable of delivering high voltages (>100 V) and large currents (>7 mA). The power supply for MEMS devices is of critical importance. Electric power can be obtained from the environment by extracting energy from mechanical motion and vibration by using piezoelectric materials; air/liquid flow by using a miniature air turbine generator; temperature gradients by using thermopiles; pH gradient by using chemical electrodes; and particle radiation by using p-n junction or other converters (Ko, 1996). MEMS devices have enabled electrically driven motors smaller than the diameter of a human hair to be realized (Huff, 2002).

Wireless sensing is becoming an integral part of civil infrastructure monitoring especially in high-performance structures where real-time information is needed to predict failure of structures and to monitor wear and strain to characterize service life (Krantz et al., 1999). These authors listed the following as some of the most desirable characteristics a wireless sensing device must have:

- Low recurring cost,
- Usable service life commensurate with the instrumented structure,
- The ability to accommodate a varying number of different types of sensors in close proximity and a varying number of similar sensors in close proximity,
- No significant effect on the instrumented structure, and
- A means to correlate the measured effects with true effects in the structure under observation.

Ong et al. (2001) have advanced an inductor-capacitor (LC) circuit for wireless sensing. Vandervoode and Puers (2001) discussed the principles on which inductive links work. The technique has been successfully used in medicine as a means of power and data transmission to implants. The drawback here is that the technology will not work where there are large amounts of electrically conductive material, such as metal, between the sensor and the monitoring antenna. Gardner et al. (2001) point out the advantage of surface acoustic wave (SAW)–based devices that are amenable to wireless interrogation and applications suitable with onboard antennas; they can be converted into sensors for use in remote inaccessible locations. Table 1 shows the common transduction mechanisms used in MEMS.

TABLE 1 Transduction Mechanisms (Adapted from Judy, 2001)

From/To	**Electrical**	**Magnetic**	**Mechanical**	**Thermal**	**Chemical**	**Radiative**
Electrical		Ampere's Law	Electrostatics	Resistive Heating	Electrolysis Ionization	EM Transmission
Magnetic	Hall Effect Mag Resistance		Magnetostatics Magnetostriction	Eddy currents	Magnetic Separation	Magneto-optics
Mechanical	Piezoresistance Piezoelectricity	Magnetostriction		Friction	Phase Change	Tribo Luminescence
Thermal	Thermoelectric	Curie Point	Thermal Expansion		Reaction Rate Ignition	Thermal Radiation
Chemical	Electrochemical Potential	Chemomagnetic	Phase Change	Combustion		Chemo-luminescence
Radiative	Photoconductor EM Receiving	Magneto-optics	Radiation Hardening	Photothermal	Photochemical	

CURRENT AND POTENTIAL APPLICATIONS

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. The transportation infrastructure fields pose special requirements and challenges for MEMS, but they also provide possibilities that cannot be exploited in other applications or fields. Sackin (1999) performed an experiment on the potential application of embedded microdevices in concrete and termed the embedded device Smart Aggregate. Sackin (1999) argued that to move beyond the limitations, power supply techniques must provide in situ measurements of local material properties throughout a structure and with a minimum of effort. Attoh-Okine (2001) discussed the potential application of MEMS in the management of infrastructure assets. That paper provided highlights of sensors and wireless monitoring applications. Mensah and Attoh-Okine (2002) explored the possibility of adopting MEMS technology for microcrack monitoring in concrete, delving into both technical and technological issues that have to be surmounted in the process. They also proposed a protocol for the application of MEMS in microcrack monitoring. Mensah and Attoh-Okine (2003) discussed both sensor communication and sensor fusion applications within MEMS applications in civil infrastructure monitoring and emphasized the importance of wireless communication of data.

Jain et al. (2002) developed a MEMS transducer for an ultrasonic flaw detection system. This experiment appears to be the first to attempt ultrasonic signal detection by MEMS transducers in direct contact with solids. This experiment was very successful. Attoh-Okine and Mensah (2002) proposed the potential applications of MEMS in pavement engineering and highlighted some of the potential applications. Attoh-Okine (2001) highlighted both the advantages and disadvantages of MEMS within pavement engineering applications. Mensah and Attoh-Okine (2003) developed an experimental protocol for the use of MEMS resonator sensors in monitoring microcracking in concrete. Obadat et al. (2003) developed full-scale MEMS-based biaxial strain transducers for monitoring the fatigue state of railway track. A unique feature of this work involves the combined use of the finite element method (FEM) and MEMS. FEM analysis was used to determine the critical fatigue locations where the MEMS transducers were to be attached to these locations. This approach can be used in many applications, since in most cases without any analysis it will be extremely difficult to know the exact position to place the MEMS device. In transportation air-quality studies, MEMS “smart dust” has the potential to collect data for both analysis and forecasting the air-quality. The groundwork for this application has already been done within the meteorological arena (Manobianco and Short, 2001). The majority of the potential MEMS applications in transportation infrastructure will act as sensors. These include sensors used in monitoring temperature, crack measurements and monitoring, corrosion testing and monitoring, alkali-silica reaction (ASR) and other related reactions in concrete, and reliability of welding units in structural steel. These classes of microsensors can be grouped as follows:

- Strain gauges that can be used to characterize the forces (during testing or monitoring) on civil infrastructure systems. The basic properties of silicon as piezoresistive material lend it to microfabrication to form a micrometer strain gauge. This is feasible especially in geotechnical testing (triaxial testing) and asphalt material testing (resilient modulus test) where every micro-strain has to be recorded. Such a system will allow for very accurate results without disturbing the test samples.

- Accelerometers that can be used as inertial sensors (Judy, 2001) can be applied in earthquake experimental studies. This inertial device usually consists of a proof mass, mechanical flexure, and displacement sensor. The MEMS fabrication process will provide an excellent way of achieving the integration. This can further be used in other vibrational and impact studies in transportation infrastructure.
- Microsensors can be used to measure pavement roughness and temperature. These sensors can be attached to simple test vehicles, so that both the temperature and the roughness of the pavement can be collected in real-time and at highway speed.
- MEMS sensors can be used in crack monitoring of bridges. The MEMS device can be used to detect the initiation of a crack. The sensors can also be used in temperature monitoring of bridges during the winter to alert drivers to the condition of bridges.
- Electrochemical MEMS sensors are capable of sensing electrochemical reactions through either potentiometric or amperometric methods. With these applications, electromechanical sensors can be used to detect and monitor corrosion in steel structures, especially welding joint and load transfer devices in rigid pavements. The potentiometric device can be used to measure and monitor equilibrium potential established between the MEMS surface and the material in contact, while the amperometric device measures the current. The electrochemical MEMS sensors material and fabrication steps depend on what one is interested in measuring and monitoring.
- Microfluidics applications can be used to identify the alkali-silica reaction, a very detrimental problem in concrete structures.

CHALLENGES

Although MEMS has great potential for many applications, some concerns have to be addressed (Maluf, 2000). To begin with, one drawback to extensive MEMS application is that MEMS products are application specific rather than generic. The vast majority of applications require solutions that necessitate the funding and completion of an evaluation or development program. In addition, 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, there is the need to carry out extensive experimentation to ascertain the reliability and consistency over time of the information obtained from the embedded devices. The impacts of the infrastructure system dynamics on the embedded device have 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 disturbs the strain field affecting the results. 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.

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 circular, an attempt is made to provide a general overview of MEMS for transportation engineers. The circular provides information on design, materials, fabrication, current and potential applications, and finally the challenges in the application of MEMS technology to transportation infrastructure systems. Although there have been successful applications of the technology in other areas of science— for example, biomedical engineering and material science— civil engineers are lagging in the use of the technology. This may be attributed to the cross-disciplinary nature of MEMS technology and, in some cases, whether civil engineers are better off using existing techniques. The only way to answer the last question is for civil engineers to attempt to use MEMS technology and compare the result to the existing approach. Furthermore, civil engineers have to determine explicitly whether the technology will be more appropriate for testing or monitoring. This circular has highlighted some challenges of using MEMS in monitoring. A few case studies in the literature demonstrate that MEMS technology has the potential to offer significant benefits to the civil engineering field.

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