SMART AIRPORT PAVEMENT INSTRUMENTATION AND HEALTH MONITORING

By:
Shuo Yang, Graduate Student
24 Town Engineering Building
Department of Civil, Construction and Environmental Engineering
Iowa State University, Ames, IA 50011-3232
Phone: +1-515-294-4698, E-mail:

Halil Ceylan, Ph.D., Associate Professor
Director, Program for Sustainable Pavement Engineering and Research (PROSPER)
406 Town Engineering Building
Department of Civil, Construction and Environmental Engineering
Iowa State University, Ames, IA 50011-3232
Phone: +1-515-294-8051, E-mail: hceylan@iastate.edu

Kasthurirangan Gopalakrishnan, Ph.D., Senior Research Scientist
354 Town Engineering Building
Department of Civil, Construction and Environmental Engineering
Iowa State University, Ames, IA 50011-3232
Phone: +1-515-294-3044, E-mail: rangan@iastate.edu

Sunghwan Kim, Ph.D., P.E., Research Assistant Professor
24 Town Engineering Building
Department of Civil, Construction and Environmental Engineering
Iowa State University, Ames, IA 50011-3232
Phone: +1-515-294-4698, E-mail: sunghwan@iastate.edu

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ABSTRACT

Realistic characterization of pavement layer properties and responses under in-situ field conditions is critical for accurate airport pavement life predictions, planning pavement management activities as well as for calibration and validation of mechanistic-based pavement response prediction models. The recent advancements in Micro-Electro-Mechanical Sensor (MEMS)/Nano-Electro-Mechanical Sensor (NEMS) technologies and wireless sensor networks combined with efficient energy scavenging paradigms provide opportunities for long-term, continuous, real-time response measurement and health monitoring of transportation infrastructure systems.

This paper presents a summary review of some recent studies that have focused on the development of advanced smart sensing and monitoring systems for highway pavement system with potential applications for long-term airport pavement health monitoring. Some examples of these potential applications include: the use of wireless Radio-Frequency Identification (RFID) tags for determining thermal gradients in pavement layers; self-powered MEMS/NEMS multifunction sensor system capable of real-time, remote monitoring of localized strain, temperature and moisture content in airport pavement that will eventually prevent catastrophic failures such as blow-ups on runways during heat waves.

INTRODUCTION

Airfield pavements are designed and constructed to provide adequate support for the various loads imposed by both aircrafts and environmental (climate) conditions such as temperature or moisture variations. In general, airfield pavements are fundamentally different from highway pavement in terms of the applied load properties. Typically, airfield pavement deals with higher load magnitude and tire pressure from airplanes, but fewer load repetitions compared to highway pavement. Although both airfield and highway pavements are prone to have deterioration from traffic and environment loads, airfield pavement usually predominately shows the environmental load related distresses rather than traffic load related ones [1].

For airport concrete pavement, one of the most common environmental related distresses is blowup [2], which is the disintegration of pavement due to axial compression force generated by slab expansion due to pavement temperature and moisture changes. It usually occurs at transverse joints or cracks in hot weather if their widths are not wide enough for concrete expansion. If pressure from concrete expansion in insufficient width cannot be relieved in time, it results in a localized upward movement of slab edges or shattering in the vicinity of the joint [3, 4, 5, and 6].

Blowup in the airport runway is very dangerous for aircraft operations and it needs immediate attention. Figure 1 presents a case of airport runway pavement blowup failure at Ankeny Regional Airport in Iowa in summer, 2011, which was reported in Central Region Airport Certification Bulletin [7]. Excessive hot weather and the associated heat wave reportedly caused the pavement blowup and buckling. As shown in Figure 2, a Raytheon Premier One jet hit the blowup spot during taking off and damaged its landing gear.

Figure 1. Blowup in Ankeny Regional Airport Runway (Photo courtesy of Snyder & Associates, Inc./Polk County Aviation Authority)

Figure 2. Damaged Aircraft in Ankeny Regional Airport Runway [7]

The other airport concrete pavement distress types caused by environmental (climate) loads in association with traffic loads include corner break, longitudinal, transverse, and diagonal cracks. These distresses can be aggravated by curling stresses induced by different thermal gradients between top and bottom parts of concrete slab.

Airport pavement distresses, when deemed detrimental to aircraft operations, can also lead to runway closure. For instance, a number of international flights in Tribhuvan International Airport in Kathmandu, Nepal were delayed, diverted and cancelled due to airport flexible pavement distress during August 2013 [8]. Figure 3 presents rutting and potholes occurring in the asphalt overlay of the runway. During the summer season of 2013, the asphalt overlay surface temperature went over 60 ˚C leading to rutting under repeated heavy aircraft loads. In the coming monsoon rain after summer season, water was accumulated on the rutting surface and then infiltrated inside the pavement through cracks. Potholes were developed from water in the underlying structure and aircraft wheel loads. As a consequence, this runway had to be closed. The impact of this event not only delivered a negative message to other countries but also caused a huge loss on their tourism business.

Figure 3. Airport Pavement Rutting (Left) and Potholes (Right) [8]

In addition to pavement distresses, the Foreign Object Debris (FOD) referred as a foreign substance or debris is considered to cause aircraft damage during its operation on airport runway [9]. Common FOD include aircraft parts, ground vehicle parts, stone, wild animals, garbage, and so on. Pavement deterioration including raveling and weathering, blowup, various cracks, corner break, popouts, and patching have significant potential to produce FOD as well [10, 11].

Pavement distresses and FOD are dangerous for aircraft operations. Once they occur on airport runways without any attention, the aircraft can be damaged during takeoff or landing and consequently the passengers inside the aircraft may be injured or lose their lives. The runway needs to be closed for repairing distresses removal of FOD. A closed runway signifies economic losses resulting from flight delays, cancellations, etc.

Pavement deterioration, as a major airport safety concern, can be controlled through in-situ pavement response and performance monitoring. In addition, realistic pavement responses from in-situ field conditions are critical for accurate airport pavement life predictions, management, calibration and validation of mechanistic-based pavement response prediction models. Real-time and continuous health monitoring and management of airport pavement systems have the potential to enable sustainable, smoother, and also safer airport infrastructure systems. This paper aims to review the state-of-the-art in smart airport pavement instrumentation and proposes a conceptual model of a smart airport pavement health monitoring system which includes MEMS-based sensors, a FOD detector, an intelligent data mapping model, as well as pavement distress and FOD warning systems.

HEALTH MONITORING OF AIRPORT PAVEMENT SYSTEMS

Needs of Airport Pavement Health Monitoring

Pavement deteriorations caused by aircraft loading, temperature, and moisture variations can be one of the major concerns in the safety of airport operations. Other pavement related safety concerns include the skid resistance (friction), FOD on pavement surface and the infiltration of water into the pavement sub-structure. Pavement health monitoring could be an effective solution to prevent the aircraft accidents and damages caused by poor pavement performance and FOD. Pavement health monitoring is an extension of the structural health monitoring (SHM) concept which employs advanced technology to allow the assessment of the structural reliability and detection of structural changes in civil infrastructure, mainly of buildings and bridges.

In recent years, with advancement in sensor and wireless technologies, SHM demonstrates that it can be applied for pavement functional and structural assessments by monitoring pavement responses and environmental conditions (temperature, moisture, etc.) in real-time. An early warning of incipient problems enabling the in-time scheduling and planning of maintenance can be provided before the appearance of remarkable structural changes to minimize unnecessary costs.

In the end, the continuously measured data can be utilized to improve distress prediction models, which can help engineers prolong the structure service life to minimize life cycle costs and the current existing defects can be corrected as well. Hence, SHM employing smart sensor system is an effective way to improve the pavement safety and to reduce maintenance cost for airfield pavement.

How to Conduct Health Monitoring of Airport Pavement Systems?

Health monitoring of airport pavement system requires smart sensing technology which can provide long term, continuous and real time monitoring of pavement conditions. In order to achieve these goals, embedded sensor interfaced with advanced wireless sensor networks is a cost-effective solution.

MEMS Sensors

The recent advancement in Micro-Electromechanical Systems (MEMS)/ Nano-Electromechanical Systems (NEMS) technologies represent an emerging solution in health monitoring for transportation infrastructure system. MEMS/NMES sensor is generally comprised of miniaturized mechanical sensing element fabricated with silicon chip. The techniques of microfabrication enable different complex electromechanical systems to be integrated in the miniaturized mechanical sensing element. Therefore, the typical dimension of MEMS devices can vary from one micron to several millimeters [12]. In addition to small size, MEMS/NEMS sensor also has high performance with relatively low energy consumption. As a result, MEMS sensors have much potential in providing cost-effective health monitoring solutions to help engineers identify pavement deterioration before the distress is noticeable to the aircrafts.

Radio-Frequency Identification (RFID) tag is a MEMS-based sensor using the radio-frequency spectrum for digital data transmission. It can be an active or passive sensing device capable of both data receiving and storing. Various RFID tag types are available for different applications.

For pavement temperature monitoring purpose, some of the commercial RFID tags available include GT-301 by GENTAG, Inc, RFID chips by RF SAW, Inc., PaveTag RFID by Minds, Inc., i-Q32T tag by WAKE, Inc., etc. Among these, the i-Q32T RFID tag has the capability to detect the inside temperature of concrete and to communicate the information to the portable Pro [13]. The i-Q32T, as shown in Figure 4, contains an internal MEMS sensor for temperature monitoring that measures and logs the temperature in definable intervals. The collected data could be imported into the portable Pro, shown in Figure 5, wirelessly for maturity calculation and saving data for posterity. The use of two-way RF communication between the buried tag and a portable Pro enables the portable Pro to read and write data.

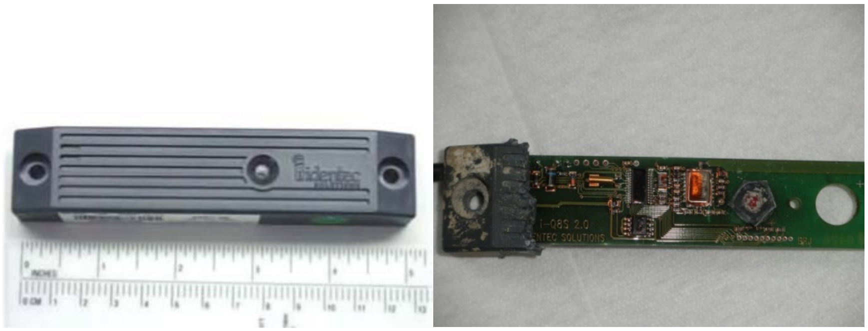

Figure 4. i-Q32T Wireless RFID Transponder (Photo courtesy of WAKE, Inc.)

Figure 5. HardTrack Portable Pro (Photo courtesy of WAKE, Inc.)

A MEMS based multifunction sensor system is currently being developed at Iowa State University (ISU) to design an integrated sensor system capable of measuring different properties such as temperature, moisture, and strain simultaneously. MEMS based multifunction sensor system can reduce installation cost and installation time which will otherwise be incurred by installation of large number of traditional single-function sensors to measure each of the properties. Moreover, if it could be integrated with a wireless transmission system, the MEMS based multifunction sensor system will not just save time and money but also improve the convenience and workability of health monitoring.

However, a truly integrated miniature multifunction sensor to detect these factors at same time is not commercially available because the device dimension and unit cost may be relatively large due to fabrication and assembling. Furthermore, it may also be more complex to implement a wireless transmission system for this kind of multifunction sensor compared to single-function sensor. Additionally, the energy consumption may be large because of measuring several parameters at the same time. One possible solution is to design an energy harvesting system by using piezoelectric materials, which can generate electric power subject to traffic loads, thunder vibrations, etc.

Wireless Networks

Traditional wired sensors generally cost more money than wireless sensors for health monitoring in civil infrastructures due to longer installation time. Furthermore, the damage and corrosion of wires in civil infrastructures is difficult to repair or replace as well. Wireless sensor technologies based health monitoring has been investigated in civil infrastructures mainly focusing on building and bridges structures.

Typical, wireless technologies available for sensor systems include Bluetooth, cellular telephony, Wi-Fi, Zigbee, and radio frequency. These technologies have different data rate, range, power consumption, ease of implementation, cost, and so on. The use of different wireless technologies also leads to the use of different wireless network topologies including star, peer-to-peer, and two-tier network [14]. Hence, the choice of the appropriate wireless technologies and networks depends on the specific environment. A robust hardware architecture and packaging for wireless sensor is also required to make wireless sensor system functional under the high alkali environment from concrete hydration and repeated vehicle loads. In addition, the limited power sources of on-site conditions can affect the working life of the wireless sensors in concrete structure. Moreover, the effective distance range of sensors in concrete should be considered as well. Typically, the longer the distance, the more power consumption there will be. It is critical to select a balance point between these factors.

Electro-optical (EO) Sensing

A FOD detection system can help airport management to detect FOD which can pose a serious threat to the safety of airport operations. An Electro-optical (EO) sensing system has been proposed as a potential solution that can detect FOD by converting light ray into electronic signal. In 2009, Stratech Systems, Ltd., developed an electro-optical sensing system called as iFerret to evaluate runway condition of Chicago O'Hare International Airport (ORD). The performance of this electro-optical sensors system was assessed and reported by various studies [11, 15, and 16]. This iFerret is an optical video based sensors system consisting of high-quality image capture system. The high resolution video sensors with zoom capabilities in the passive sensing system were mounted in several towers to ensure it to sweep a large scan area continuously. Furthermore, the video sensor can scan the pavement surface almost up to 1,100-ft by using ambient lighting conditions [15]. All the sensors in the system interfaced with image-processing software are networked to the central console located in the air traffic control tower. The iFerret system detects the FOD by interpreting the data collected by the electro-optical sensors and then sends an alert to the operator if an FOD is detected. The location and video image of the FOD will be also sent to the operator to confirm. As a consequence, hazard assessment and clear-up work can be processed.

Figure 6. iFerret Electro-optical Sensor at Chicago O'Hare International Airport
(Source : iFerret™, http://www.stratechsystems.com/iv_iferret.asp)

HEALTH MONITORING OF PAVEMENTS: EXAMPLES

Runway Instrumentation at Denver International Airport

In the 1990s, the runway construction at Denver International Airport (DIA) included a comprehensive instrumentation of strain gages, Thermocouples, and Time Domain Reflectometrs (TDR). A total of 460 sensors were instrumented in the sixteen slabs in the runway to monitor the pavement response generated from aircraft wheel and environment loading. Among the installed sensors, dynamic sensors measured stain, vertical displacement, airplane speed and acceleration when an airplane pass triggered the sensors. A data acquisition system (DAS) was placed in-situ for data collection and downloading to an ORACLE7 database managed by FAA technical center to analyze aircraft and pavement data. Furthermore, the performance of this system was also assessed later by Dong [17], Lee [18], Rufino [19], etc.

Optical Fiber Sensors in Kai-Shek International Airport

In 2002, Chou and Chen [20, 21] conducted a study at Chiang Kai-Shek (CKS) International Airport in Taiwan to monitor pavement joint movements and thermal stresses at one taxiway. In this study, several different types of dynamic and static strain gauges were installed in concrete pavements. Dynamic strain gauges in this study include H-bar strain gauges, dowel bar strain gauges, and gear position gauges. For static strain gauges, optical fiber sensors and thermal sensors were installed. The Smartec SOFO optical fiber sensors measured concrete joint movements (expansion and contraction). The optical fiber sensors were tied to the rebar racks before concrete paving and they started recording data after concrete paving with a 20 minute interval. A DAS was connected to optical fiber for data transmission.

(a) (b)

Figure 7. (a) SOFO Optical Fiber Sensor, (b) DAS System [21],

Piezoelectric Strain Sensor for Smart Asphalt Pavement Monitoring

Lajnef et al. [22] investigated a wireless piezoelectric strain sensor system to estimate fatigue damage for asphalt pavements in 2013. A wireless integrated circuit sensor was interfaced with a piezoelectric transducer for relatively low energy consumption. The piezoelectric transducer had an array of ultra-low power floating gate (FG) computational circuits to supply sensor operating power from vehicle movements. The sensor could measure strain change and store the data on-board for periodical transmission trough RF. A central database was required to receive the uploaded data from sensors. A RF reader mounted on a moving vehicle could be used to read and download the data from the sensor as well.

Figure 8. Prototype Installation of Self-powered Strain Sensor [22]

Wireless MEMS System for Concrete Moisture Monitoring

Figure 9 compares the wired MEMS scheme for in-situ concrete moisture monitoring with a wireless MEMS scheme in a recently completed study conducted by the authors and collaborators from the electrical engineering department at ISU. In the working scheme of wired MEMS scheme, the sensor should be connected to the data reader and the computer through cables to continuously monitor the concrete properties and download the data. As a consequence, both the data reader and the computer require electrical supply for operations. However, the wireless system does not require any external cables which can save installation time and reduce the risk of malfunction of sensors.

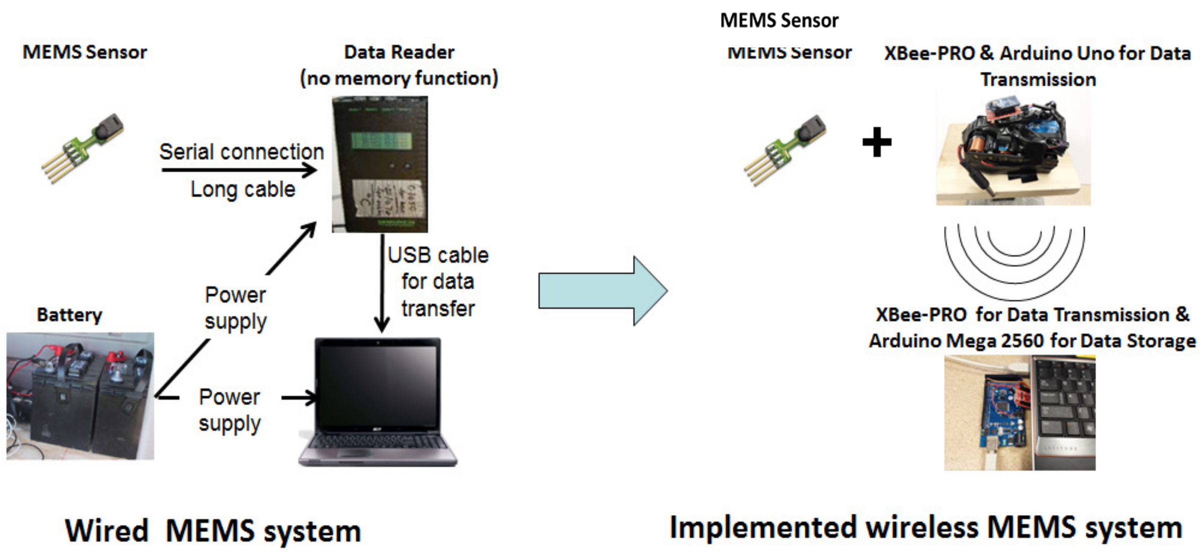

Figure 9. Comparison between Wired MEMS based Moisture Sensor System and Wireless MEMS based Moisture Sensor System

A CONCEPTUALSMART AIRPORT PAVEMENT HEALTH MONITORING

A health monitoring and management system for airport pavements could provide in-situ pavement conditions and responses to prevent multi-faceted safety concerns including pavement deteriorations and FODs from aircraft operations.

Figure 9 illustrates a conceptual design of airport health monitoring system. In this figure, the embedded smart MEMS sensor subsystem is a wireless multifunction MEMS which can measure strain, temperature, and moisture simultaneously. The robust packaging subsystem should be implemented to protect the embedded smart MEMS sensors during installation and operation under harsh climatic and traffic conditions. The smart MEMS sensor subsystem can be integrated with EO based distress and FOD detectors to monitor actual pavement surface condition. A reliable data acquisition subsystem mounted on a moving vehicle or control tower can be used to collect, store, and transfer data from MEMS sensors and EO based detectors. The intelligent data mapping model subsystem employing sensing data fusion and geo-spatial analysis approach can be utilized in data mapping of entire section from collected data from sensor installed in specific locations. Realistic characterization of pavement layer properties and responses through intelligent data mapping model subsystem can be utilized for early warning of critical distress initiation, accurate airport pavement life predictions, planning pavement management activities as well as for calibration and validation of mechanistic-based pavement response prediction models.

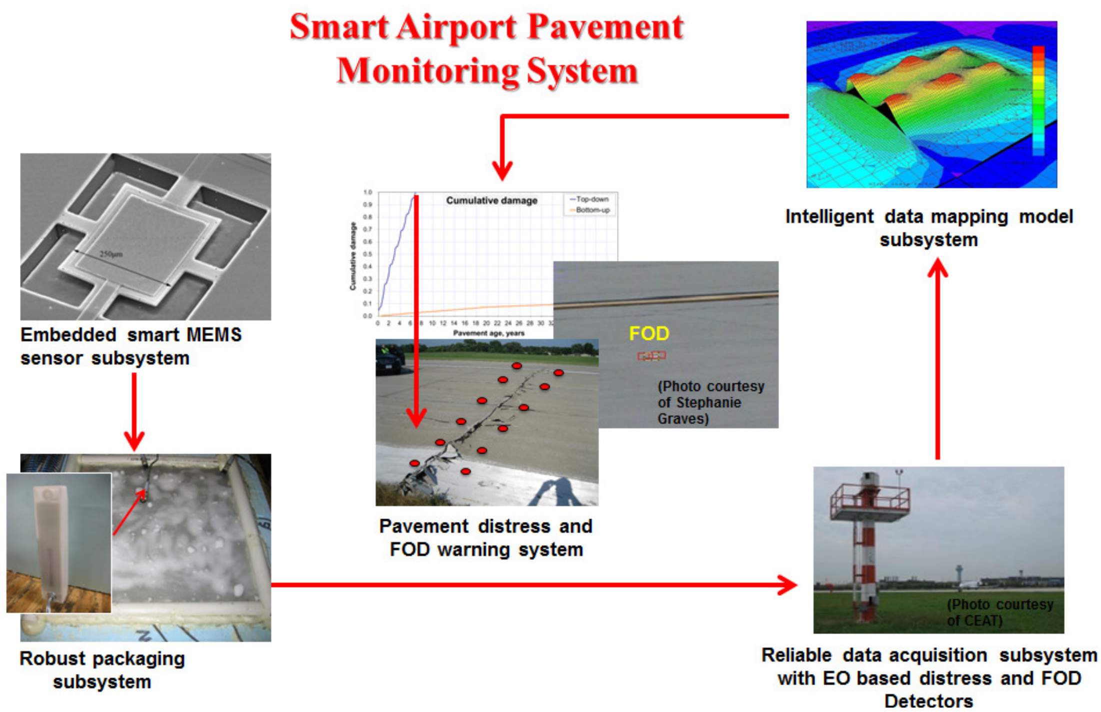

Figure10. Conceptual Smart Health Monitoring of Airport Pavement Systems

SUMMARY

The recent advancements in Micro-Electro-Mechanical Sensor (MEMS)/Nano-Electro-Mechanical Sensor (NEMS) technologies and wireless sensor networks combined with efficient energy scavenging paradigms provide opportunities for long-term, continuous, real-time response measurement and health monitoring of airport pavement systems. MEMS/NEMS represent an innovative solution in airport pavement condition monitoring that can be used to wirelessly detect and monitor structural health (damage initiation and growth) as well as functional health in airport pavement structures. Static or dynamic sensors, such as strain gauges or pressure cells, have also been used in new or existing airport pavements, but are mostly restricted to experimental studies on a short-term basis. The required properties for health monitoring of airport pavement systems include multifunction sensing capacity, wireless communications, lower energy consumption for operation, robust packaging, reliable data acquisition, intelligent data mapping, and early warning of critical distress initiation. Such health monitoring of airport pavement systems is crucial for:

- Maintaining the structural and functional performance for safe aircraft operations

- Providing optimal timing of maintenance/rehabilitation activities and efficient allocation of scanty resources

- Understanding complex pavement system behavior to achieve sustainable airport pavement systems

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REFERENCES

1. Federal Aviation Administration, U.S. Department of Transportation, “Development of Standards for Nonprimary Airports,” Advisory Circular AC 150/5100-13B, 2011.
2. Lary, Jo, “Airport Pavement Maintenance and Management,” Airfield Safety, Sign Systems and Maintenance Management Workshop, Pavement Consultants Inc., April 2009.
3. Applied Pavement Technology, Inc., “Creston Municipal Airport Pavement Management Report,” Iowa Department of Transportation, Office of Aviation, December 2011.
4. Applied Pavement Technology, Inc., “Washington Airport Pavement Management System-Pavement Management Manual,” Washington State Department of Transportation Aviation, Arlington, WA, July 2013.
5. Federal Aviation Administration, U.S. Department of Transportation, “Guidelines and Procedures for Maintenance of Airport Pavements,” Advisory Circular AC 150/5380-6B, 2007.
6. Garg, Navneet; Guo, Edward; and McQueen, Roy, “Operational Life of Airport Pavements,” Technical Report DOT/FAA/AR-04/46, U.S. Department of Transportation, Federal Aviation Administration, Office of Aviation Research, Washington, DC, December 2004.
7. Mullen, Mike, “Special Inspections of Paved Areas During Excessive Heat Periods,” Central Region Airport Certification Bulletin, Federal Aviation Administration, Central Region, Airports Division, Kansas City, MO, July 2011.
8. Nepal, Shailesh, “TIA Runway Overlay Project Failure: A Case Study from Nepal,” *PM World Journal*, Vol. 3, Issue. 5, 2014.
9. Ang, Li, “Research and Design of an Airfield Runway FOD Detection System Based on WSN,” *International Journal of Distributed Sensor Networks*, Hindawi Publishing Corporation, 2013.
10. Federal Aviation Administration, U.S. Department of Transportation, “Airport Foreign Object Debris (FOD) Detection Equipment,” Advisory Circular AC 150/5220-24, 2009.
11. Graves, Stephanie W., “Electro-optical Sensor Evaluation of Airfield Pavement,” Thesis, University of Illinois at Urbana-Champaign, Urbana, IL, 2012
12. MNX, *What is MEMS Technology*. https://www.mems-exchange.org/MEMS/what-is.html. 2014.
13. Ceylan, Halil; Gopalakrishnan, Kasthurirangan; Taylor, Peter; Shrotriya, Pranav; Kim, Sunghwan; Prokudin, Max; Wang, Shiyun; Buss, Ashley F.; and Zhang, Jiake, “A Feasibility Study on Embedded Micro-Electromechanical Sensors and Systems (MEMS) for Monitoring Highway Structures,” Technical Report IHRB Project TR-575, National Concrete Pavement Technology Center, Ames, IA, June 2011.

14. Lynch, Jerome P.; and Loh, Kenneth J., “A Summary Review of Wireless Sensors and Sensor Networks for Structural Health Monitoring,” *The Shock and Vibration Digest*, Vol. 38, No. 2, pp. 91–128, 2006.
15. Herricks, Edwin E.; Lazar, Peter; Woodworth, Elizabeth; and Patterson, James, “Performance Assessment of An Electro-optical-based Foreign Object Debris Detection System,” Technical Report DOT/FAA/AR-11/13, U.S. Department of Transportation, Federal Aviation Administration, William J. Hughes Technical Center, Aviation Research Division, Atlantic City International Airport, NJ, March 2012.
16. Lazar, Peter; and Herricks, Edwin E., “Procedures for FOD Detection System Performance Assessments: Electro-optical FOD Detection System,” FAA Worldwide Airport Technology Transfer Conference, Atlantic City, NJ, April 2010.
17. Dong, Mingyao; and Hayhoe, Gordon F., “Denver International Airport Sensor Processing and Database,” Technical Report DOT/FAA/AR-00/17, U.S. Department of Transportation, Federal Aviation Administration, Office of Aviation Research, Washington, DC, March 2000.
18. Lee, Xiaogong; Hovan, Michel; King, Ryan; Dong, Mingyao; and Hayhoe, Gordon F., “Runway Instrumentation at Denver International Airport Development of Database,” *Aircraft/pavement technology: in the midst of change*, pp. 348, 1997.
19. Rufino, Dulce; Roesler, Jeffery; and Barenberg, Ernest, “Mechanistic Analysis of Pavement Responses from Denver International Airport,” FAA Center of Excellence (COE) for Airport Technology Report No.26, Department of Civil and Environmental Engineering, University of Illinois at Urbana-Champaign, IL, January 2004.
20. Chou, Chia-Pei.; Cheng, Hsiang-Jen; and Lin, Shyh-Tai, “Analysis of Concrete Joint Movements and Seasonal Thermal Stresses at the Chiang Kai-Shek International Airport,” FAA Worldwide Airport Technology Transfer Conference, Atlantic City, NJ, USA, April 2004.
21. Wang, Chung-Yue; Wang, Hao-Lin; and Chen, Ming-Hung, “Structural Health Monitoring Activities of Applying Optical Fiber Sensors in Taiwan,” International Workshop on Structural Health Monitoring and Damage Assessment, National Chung Hsing University, Taichung, Taiwan, ROC, December 14-15, 2006.
22. Lajnef, Nizar; Chatti, Karim; Chakrabartty, Shantanu; Rhimi, Mohamed; and Sarkar, Pikul, “Smart Pavement Monitoring System,” Technical Report FHWA-HRT-12-072, U.S. Department of Transportation, Federal Highway Administration, Research, Development, and Technology Turner-Fairbank Highway Research Center, McLean, VA, May, 2013.