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WIRELESS SENSING TECHNOLOGIES FOR PRE-EARTHQUAKE EVENT MITIGATION AND POST-EARTHQUAKE EVENT RESPONSE

J. P. Lynch[1]

ABSTRACT

The rapid growth of wireless communication technology is having a profound impact on the field of earthquake engineering. In particular, wireless sensors are sufficiently mature that they can now be used to assess the behavior and condition of civil structures before, during and after a seismic event. Structural health assessment offers opportunities to evaluate risk prior to the occurrence of an earthquake and to rapidly assess structural conditions immediately following a major seismic event. Furthermore, current research in the smart structure community is focused on the extension of the wireless monitoring paradigm to include actuation capabilities. Wireless nodes can be used in the architectural design of future structural control systems that mitigate undesired structural responses during seismic events. Other wireless devices such as cellular phones have the potential to offer the earthquake engineering community opportunities to passively collect information on people in order to optimize emergency response efforts after a major earthquake event.

Introduction

The rapid advancement of wireless communication technology has beneficially impacted many aspects of everyday life in modern societies. For example, wireless networks provide the convenience of allowing individuals to connect their personal computers to the internet without the need for a tethered connection. Another example is the cell phone; cell phones offer the convenience of anytime, anywhere access to telephony services. The recent generation of "smart" cell phones also illustrates the utility of sophisticated software applications that store personal information (*e.g.*, contacts, calendar) on the phone, utilize sensors embedded in the phone (*e.g.*, GPS positioning on maps) and offer internet-enabled tools such as email and texting. These technological advances are also enabling a new generation of untethered sensors and data collection tools that will ultimately improve the earthquake engineering field's ability to mitigate earthquake vulnerabilities while improving post-earthquake event responses. This paper will focus on three specific wireless technologies that directly impact the earthquake engineering field: wireless monitoring systems, wireless feedback control systems, and cellular phones as a data collection tool. The paper complements the panel discussion titled, "Using Technology to Influence Individual, Social, Organizational, and Community Behavior Before and After an

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[1] Associate Professor, Dept. of Civil and Environmental Engineering, University of Michigan, 2380 G. G. Brown Building, Ann Arbor, MI 48109-2125; jerlynch@umich.edu

Earthquake Event," and represents the perspectives of the author who has been invited to serve as a panel participant. The paper will first provide a brief introduction to each of the three wireless technologies as they relate to earthquake risk mitigation and post-earthquake event response. The paper then presents the author's response to three questions posed by the moderator to the panel participants. The paper closes with conclusions and identification of future research directions necessary to advance wireless telemetry within earthquake engineering applications.

Wireless Sensors

The monitoring of large structures in seismic regions is often recommended by local building codes to ensure ground motion and structural response data is available for continual code improvement. For example, the 2001 California Building Code mandated structures with heights over 6-stories or with total floor areas of 60,000 ft^2 be instrumented with a minimum of three accelerometers. The U.S. General Services Administration (GSA) makes similar recommendations for federal buildings located in seismic zones (GSA 2003). In California, even instrumented buildings must remain unoccupied until they can be inspected by a local building official. Unfortunately, inspections might not occur for many hours, or even days after a seismic event. Furthermore, high inspection costs were cited after the 1994 Northridge Earthquake especially for steel moment resisting frame buildings (Hamburger 2000). To accelerate the time to re-occupancy, municipalities such as the City of San Francisco are adopting programs allowing owners to retain pre-qualified engineers that can decide on occupancy based on post-event inspections and analysis (Celebi, *et al.* 2004). As these re-occupancy programs continue to grow, demand for structural instrumentation will rise since monitoring provides empirical evidence vital to the re-occupancy decision making process.

Building instrumentation entails the installation of sensors throughout a structure that measure structural responses to strong ground motion. Architecturally, such monitoring systems are highly centralized with sensors connected to a single data server through coaxial wiring. The sensors utilized for monitoring the response of the structure can vary, but force-balanced accelerometers remain one of the most common sensors adopted. The cost of the system components and installation is quite high; recent experiences reported by the United States Geological Survey (USGS) report costs as high as $5,000 per sensing channel (Celebi 2002). In particular, the installation process (including the routing of coaxial wiring in the structure) can represent more than 25% of the total system cost (Straser and Kiremidjian 1998).

In the mid-1990's, Straser and Kiremidjian (1998) at Stanford University first proposed the replacement of traditional coaxial wiring with wireless communications. Recognizing that high installation costs was a major impediment to widespread adoption of structural monitoring systems, their wireless monitoring approach would offer structural owners opportunities to install instrumentation at substantially reduced costs. Since that time, wireless sensor technology has rapidly matured into a reliable substitute for tethered sensors in a wide host of applications including structural monitoring (Lynch and Loh 2006). As shown in Figure 1, a large number of wireless sensors have now been developed that can be used for structural monitoring including sensors developed by academic and industrial groups. Many of the wireless sensors presented in Figure 1 have been successfully instrumented on large-scale civil structures including highway bridges (Lynch, *et al.* 2006), suspension bridges (Pakzad, *et al.*

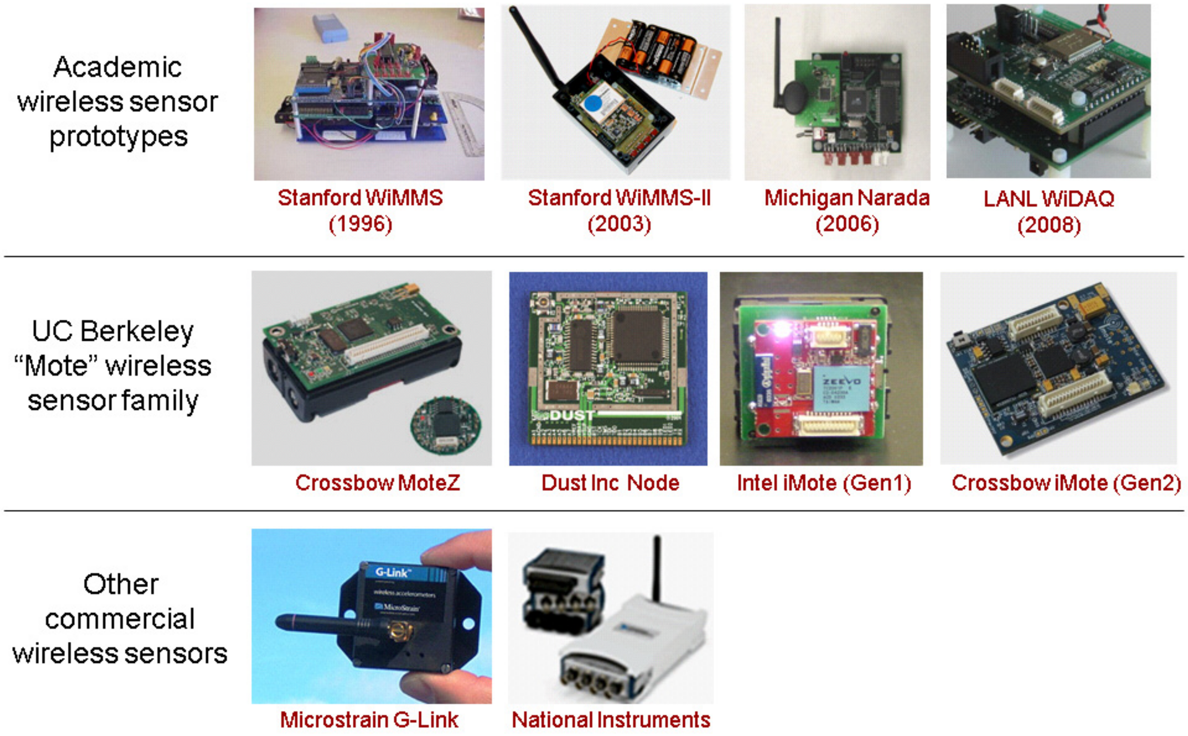

Figure 1. Wireless sensors proposed for monitoring civil structures. Top row consists of prototypes proposed by the academic structural engineering community. Middle row corresponds to commercial wireless sensors originating from an open-source wireless sensor platform developed at University of California Berkeley. The bottom row represents other commercial prototypes proposed for structural monitoring.

2008), cable-stayed bridges (Lu, *et al.* 2006), buried pipelines (Lee, *et al.* 2009) and buildings (Zimmerman, *et al.* 2008).

While the historical motivation of wireless sensors was to offer a low-cost instrumentation platform for structural monitoring, wireless sensors today offer functionalities that far exceed those associated traditional sensors. In particular, wireless sensors are designed with a low-power microcontroller integrated; the microcontroller converts data collected by an analog-to-digital converter into packets required by the wireless radio for transmission. This microcontroller (with its associated arithmetic and logic unit (ALU) and on-chip memory) also represents computational power accessible to the sensor. Unlike traditional sensors that pass analog sensor readings to the centralized data repository, the embedded computing capabilities of wireless sensors allow them to process and interrogate their own raw measurements. The implications of this local computing capability are enormous for the earthquake engineering community. Local data processing by the sensor will prove to be a scalable approach to management of data within the monitoring system. Instead of inundating end-users with raw data at a data server (as is the case in traditional monitoring systems), wireless monitoring systems can pre-screen data at the node-level so that data can be autonomously analyzed and prioritized for manual review by a professional engineer. Algorithms that can assess the real-time condition of a structure can also be vital to accurately calculating risk levels associated with a structure in different earthquake scenarios. Rapid assessment of structural conditions after an earthquake can also assist with the decision making process executed by first-responders and engineers engaged in re-occupancy analyses.

Wireless Feedback Control Systems

Structural control systems were first proposed by Yao (1972) but did not begin to be commercially implemented until a decade later (Soong 1990). Early attempts at structural control concentrated on the development of "active" control systems that used large actuators and masses to control a structure. These active control approaches suffered from some technological drawbacks including high power demands and single-point of failure concerns. By the early 1990's, the structural engineering field began to move away from active control approaches and toward the use of semi-active control devices (*e.g.,* semi-active damper systems) that consume significantly less power and are proven to be more reliable over long periods of operation. Today, many structures worldwide have been instrumented with semi-active variable dampers that optimally control lateral structural responses by removing seismic energy from the structure (Kurata, *et al.* 1999). Since semi-active control devices are smaller devices, large buildings utilizing them for seismic response control may require hundreds of these semi-active devices.

While great advances have been made in structural control, structural control systems still rely on the use of coaxial wiring for communication between sensors, actuators and the centralized controller (the controller calculates optimal control actions for the actuators based on response measurements collected from sensors). Due to wiring requirements, control systems grow prohibitively expensive when there are a large number of sensors and actuators in the system. As a result, control systems consisting of hundreds of semi-active variable dampers often abandon the traditional centralized system architecture for decentralized architectures. The decentralized approach integrates sensors and a controller with each semi-active actuator; no communication is facilitated between devices. Therefore, each device calculates its control actions based on only its local structural response measurement (Kurino, *et al.* 2003).

Wireless communications can be used to enhance the capabilities of semi-active control systems, especially those in which no communication between independent control devices is permitted. To this end, researchers are exploring the design of low-cost wireless sensor nodes that can command semi-active control devices using digital-to-analog converters integrated into their design (Lynch 2005; Wang, *et al.* 2006). In a wireless structural control system, wireless sensors can be used to simultaneously collect structural response measurements, communicate measurements to the wireless network, calculate control actions based on measurements collected locally and those obtained wirelessly from other nodes, and issue commands to system actuators. Recent research conducted at the National Center for Research in Earthquake Engineering (NCREE), Taipei, Taiwan has explored the implementation of wireless control systems on a partial-scale steel frame structure in which magnetorheological (MR) dampers have been installed on each of the structure's six stories (Figure 2). Wireless sensors with actuation capabilities have been installed on each story to collect lateral accelerations and to command each MR damper (Wang, *et al.* 2007; Loh, *et al.* 2007; Swartz and Lynch 2009).

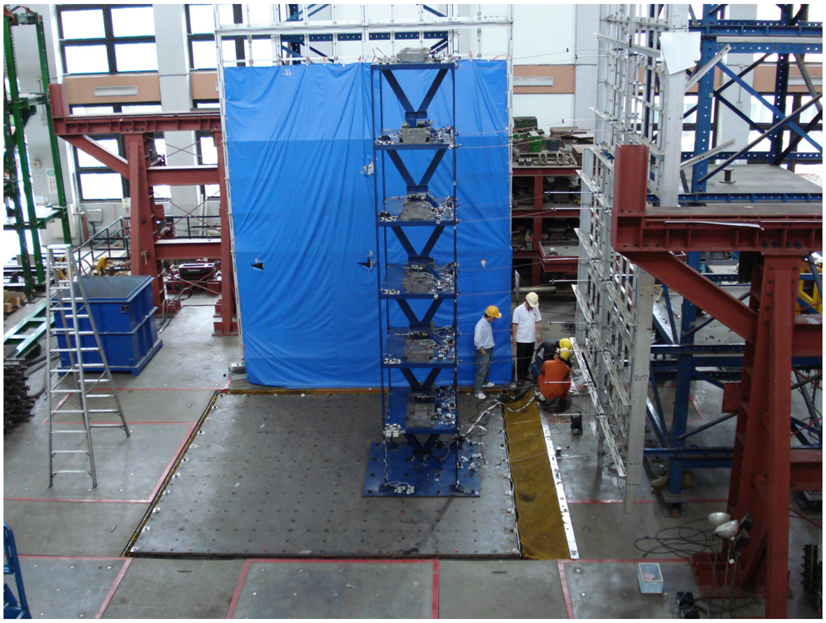

Figure 2. Six-story steel frame structure mounted on a six degree of freedom shake table at the National Center for Research on Earthquake Engineering (NCREE), Taipei, Taiwan. One MR damper is installed on each story using a V-brace. Wireless sensors are coupled with each MR damper to measure story accelerations, communicate measurements, calculate control forces and issue commands to the MR dampers.

Cellular Networks as a Sensor Network

Worldwide, there are currently 4 billion mobile phones in use for voice and data communications (UNESCO 2008). The current generation of mobile phones even contain on-board sensors (for example, global positioning sensors (GPS) and accelerometers). As a result, the global network of cell phones is capable of being used as a powerful global data-collection network (Economist 2009). Currently, these data-collection networks are only starting to be recognized as a tool for sensing society. Non-profit InSTEDD (Innovative Support to Emergencies, Diseases and Disasters) and for-profit Sense Networks both are exploring means of collecting (passively and actively) data and information from cell phone users to assist emergency response efforts to pandemics and natural calamities such as earthquakes (Economist 2009). For example, cell phones can serve as a basis for determining the number, location and state of structural inhabitants following an earthquake. Other mobile phone sensor modalities including sound, picture and video open additional data types that could contribute to first responder's post-event decision making. While comparatively little research has been conducted on the use of cell phones, their ubiquitous availability renders them a potentially powerful, yet untapped data source for the earthquake engineering community.

Responses to the Questions Posed to the Panel

What technologies show the greatest promise for significantly improving pre-earthquake event mitigation, and/or post-earthquake event response and recovery?

Among the aforementioned wireless technologies, wireless sensors show the greatest promise for improving pre-earthquake event mitigation and post-earthquake event response. Wireless sensors have been under development for more than a decade with current wireless sensors costing an order of magnitude less than tethered counterparts. Wireless communications have also improved in recent years with wireless sensors now offering reliable, long-range communication in harsh radio frequency (RF) environments. In addition, current efforts focused on embedding computational algorithms into the computational cores of wireless sensors will ultimately lead to sensors capable of individually and collaboratively processing measurement data. In-network data processing has the potential to provide decision makers with actionable information upon which decisions can be made (this is in contrast to the glut of raw data commonly provided by current monitoring systems).

What are the biggest problems or impediments that must be overcome to effectively implement these technologies?

While wireless sensors have already been deployed for short-term (*i.e.*, weeks) monitoring studies of operational structures, some functional limitations must be addressed before wide-spread commercial adoption is possible. Currently, power remains the greatest challenge for the long-term (*i.e.*, decades) use of battery-operated wireless sensors. Fortunately, power harvesting technologies have the potential to solve this technology bottleneck. Research efforts are begging to yield vibration-, thermal-, and solar-based power harvesters capable of alleviating some of the power constraints of wireless sensors. However, significantly more research is need to fully mature power harvesting technology into a viable power solution.

The aforementioned advances in sensing and telemetry technology now make it possible to install dense sensor networks (potentially, hundreds of sensors) in civil infrastructure systems. However, an important question to ask is, “what does one do with all of the data that can be created by these ubiquitous sensing environments?” Unfortunately, the tools necessary for data interrogation have not kept pace with the rapid development of the sensing and telemetry technologies that make the data possible. Damage detection using sensed data is a challenging inverse problem. The current state-of-practice is to update physics-based models to identify changes in the underlying structural properties. However, these approaches have not proven sufficiently robust to identify damage with low levels of false-positives and false-negatives. In response to these limitations, the field is beginning to explore new approaches to data interrogation. Specifically, new research aimed at using data mining, machine learning, and pattern classification methods for identifying subtle changes in data correlated to structural distress is being pursued.

What are the social, cultural, political, and environmental consequences of using these technologies?

The payoffs associated with using wireless telemetry in future structural monitoring and control systems can be large. First, low-cost wireless sensors can be installed in greater density in a single structure compared to tethered sensors. Greater spatial densities of sensors will inevitably provide the engineering community with richer data sets from which seismic deign codes can be improved. In particular, greater empirical evidence of structural performance during seismic events will be vital for the field's movement toward performance-based design methods. Second, rapid identification of structural distress after an earthquake can warn first responders of impending structural collapse. This can save the lives of first responders if a structure is near collapse. Finally, tracking the condition of structures will greatly benefit the insurance industry; the availability of response data before and after seismic events will allow the industry to evaluate structural vulnerabilities more accurately and to identify seismic-induced damage from pre-existing damage.

There are some social and political consequences to utilizing mobile phones as a sensing platform for tracking individuals after a seismic event. Even for passive tracking of mobile phones (passive tracking protects the identity of the tracked mobile phone user), privacy concerns will prompt public resistance to such technologies. However, the benefits of identifying trapped inhabitants in collapsed buildings must be balanced with these privacy concerns.

Conclusions

The emergence of wireless communication technology is rapidly changing the field of earthquake engineering. Wireless sensors have the potential of monitoring structures before, during and after seismic events leading to rich sets of measurement data from which design codes can be improved and structural health assessed. In addition, the extension of the wireless monitoring paradigm into the area of structural control is leading to low-cost structural control systems capable of more effective control solutions. The end result is safer structures that experience lower levels of seismic damage. Finally, devices like mobile phones offer opportunities to track individuals during earthquakes so as to provide information to first responders on trapped and incapacitated structural inhabitants. While the benefits associated with wireless sensing technology are many, some technological and political challenges exist. For example, improved methods of automated data interrogation are direly needed to allow engineers to derive information from data sets. Furthermore, the earthquake engineering community will need to articulate how the benefits of tracking the public via their mobile phones offset valid privacy concerns.

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